EVALUATION OF PROTECTION SCHEMES FOR ULTRAHIGH-STRENGTH STEEL ALLOYS FOR LANDING GEAR APPLICATIONS

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ABSTRACT

The use of ultrahigh-strength steel alloys is required to meet the performance and weight requirements for landing gear. Historically, there has not been a corrosion resistant alloy available that meets the strength requirements and provides adequate corrosion protection. Therefore, the use of cadmium coatings has been the preferred method of corrosion protection in landing gear systems for decades. In recent years, a new ultrahigh-strength corrosion resistant alloy has been developed (UNS S10500) that has potential to reduce or eliminate the use of cadmium coating within landing gear systems. A comparison of various protection schemes (primer and paint only, zinc-nickel, and cadmium) for this new alloy were compared to other ultrahigh-strength steels (UNS G43400, UNS K44200, UNS K92580, and UNS K91973) using their currently recommended protection schemes for landing gear (primarily cadmium). Salt fog testing per ASTM B117 using scribed panels was the basis for this study. Scribe widths of approximately 0.5 mm and 2.5 mm were exposed for times of 100 and 500 hours. Results indicate that the cadmium coating starts to break down at approximately 100 hours, and small areas of iron oxide corrosion product are present on the low-alloy steels, while no rust is observed for the high-alloy and corrosion-resistant alloy. The zinc-nickel coating evaluated provides adequate corrosion protection up to 500 hours, but experiences blistering. The prime and paint only scheme of the corrosion resistant alloy showed localized pitting and rust product, while other areas of the exposed region were protected by a passive chromium-oxide layer.

Keywords: Ultrahigh-strength steel, corrosion, ASTM B117, landing gear, UNS S10500, UNS K91973

INTRODUCTION

Each year, the Air Force's Ogden Air Logistics Center (OO-ALC) condemns nearly $300 million of steel landing gear components (1). These components are victims of hydrogen embrittlement, corrosion, and stress corrosion cracking associated with alloys currently in use for landing gear. The cost associated with the condemned hardware is accompanied by a significant environmental burden. OO-ALC

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUL 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Evaluation of Protection Schemes for Ultrahigh-Strength Steel Alloys for Landing Gear Applications**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **QuesTek Innovations LLC,1820 Ridge Avenue,Evanston,IL,60201**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**41**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

produces more than 2,000 lbs of toxic cadmium during landing gear overhauls. With military aircraft operating at unprecedented levels, the stress placed on landing gear in the field and on the system to support them is creating an environment in which both cost and product availability are essential concerns.

Historically, in selecting alloys for use in landing gear there is a trade-off between weight and corrosion resistance. Stainless steel alloys that provide adequate corrosion protection to alleviate the use of cadmium do not provide adequate strength to meet weight requirements, whereas traditional ultrahigh-strength steel alloys used to meet the weight requirements do not provide adequate corrosion protection and require a sacrificial coating, such as cadmium. In recent years, a new approach to this issue was pursued through design of a new ultrahigh-strength corrosion resistant alloy. This new alloy has the potential to reduce or eliminate the use of cadmium coatings in landing gear applications. The nominal composition and strength value for each alloy evaluated is shown in TABLE 1 below.

TABLE 1 NOMINAL COMPOSITION AND STRENGTH OF ALLOYS USED IN COMPARISON STUDY

Specification	Nominal Composition (wt%)	Ultimate Strength (MPa)
UNS G43400 (AMS 6414)	0.80Cr - 1.8Ni - 0.25Mo (0.38 - 0.43C)	1793 - 1931
UNS K44220 (AMS 6257)	1.6Si - 0.82Cr - 0.40Mo - 0.08V (0.40 - 0.44C)	1931 - 2103
UNS K92580 (AMS 6532)	3.1Cr - 11.5Ni - 13.5Co - 1.2Mo (0.21 - 0.25C)	1931 - 2103
UNS K91973 (AMS 6516)	1Cr - 10Ni - 7Co - 2Mo - 1.3W - 0.1V (0.28 - 0.32C)	1931 - 2103
UNS S10500 (AMS 5922)	10Cr - 5.5Ni - 14Co - 2Mo - 1W (0.19 - 0.23C)	1931 - 2103
UNS S15500 (AMS 5659)	15Cr - 4.5Ni - 0.30Nb - 3.5Cu	1310

EXPERIMENTAL PROCEDURE

A comparison of five commercially available ultrahigh-strength steel alloys (UNS G43400[1], UNS K44220[2], UNS K92580[3], UNS K91973[4], and UNS S10500[5]) that are intended for use in landing gear applications were evaluated using 6.5 x 100 x 150 mm panels using the recommended protection schemes that contained ‘X’ scribes of approximately 0.5 mm and 2.5 mm per ASTM B117 salt fog testing in 100 and 500 hour time increments. A high-strength stainless steel (UNS S15500[6]) was also used in the 500 hour test for comparison.

Each panel was prepared in accordance with landing gear manufacturing processes. A detailed outline of the process used for each alloy is shown in TABLE 2 below. Scribes were introduced to the panels after painting. With a scribing tool not fully developed to produce uniform scribes of approximately 2.5 mm, an aluminum-oxide grinding wheel was dressed to produce the desired widths. This approach was used for both the 0.5 mm and 2.5 mm scribe widths to provide accurate comparisons. Two scribes, one

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[1] 4340
[2] 300M
[3] AerMet® 100
[4] Ferrium® M54™
[5] Ferrium S53®
[6] PH15-5

at 0.5 mm and one at 2.5 mm width, were set side by side on one face of each test panel, as shown in FIGURE 2. The grinding wheel was operated at 3600 RPM and removed approximately 0.01 mm per pass until the base metal was exposed. An acetone rinse of each scribe line was then completed. Some panels were damaged during preparation and a polymer was used to mask exposed areas outside of the scribe lines. Images were taken to document the pretest condition of each test panel.

The scribed test panels were then placed into a salt fog chamber at an angle of 15 degrees (from the normal vertical axis) with the scribed face of the panels facing upward. An image of test setup is shown in Figure 1 below. The testing was completed per ASTM B117 using 5% NaCl solution at 35°C for durations of 100 and 500 hours. Samples were then removed from the chamber, rinsed to remove any residual salt formation, and dried. Images were taken to document the post test condition of each panel. Each panel was then examined using a scanning electron microscope (SEM) to determine if any corrosion product was present and if any blistering or undercutting of the protection scheme had occurred.

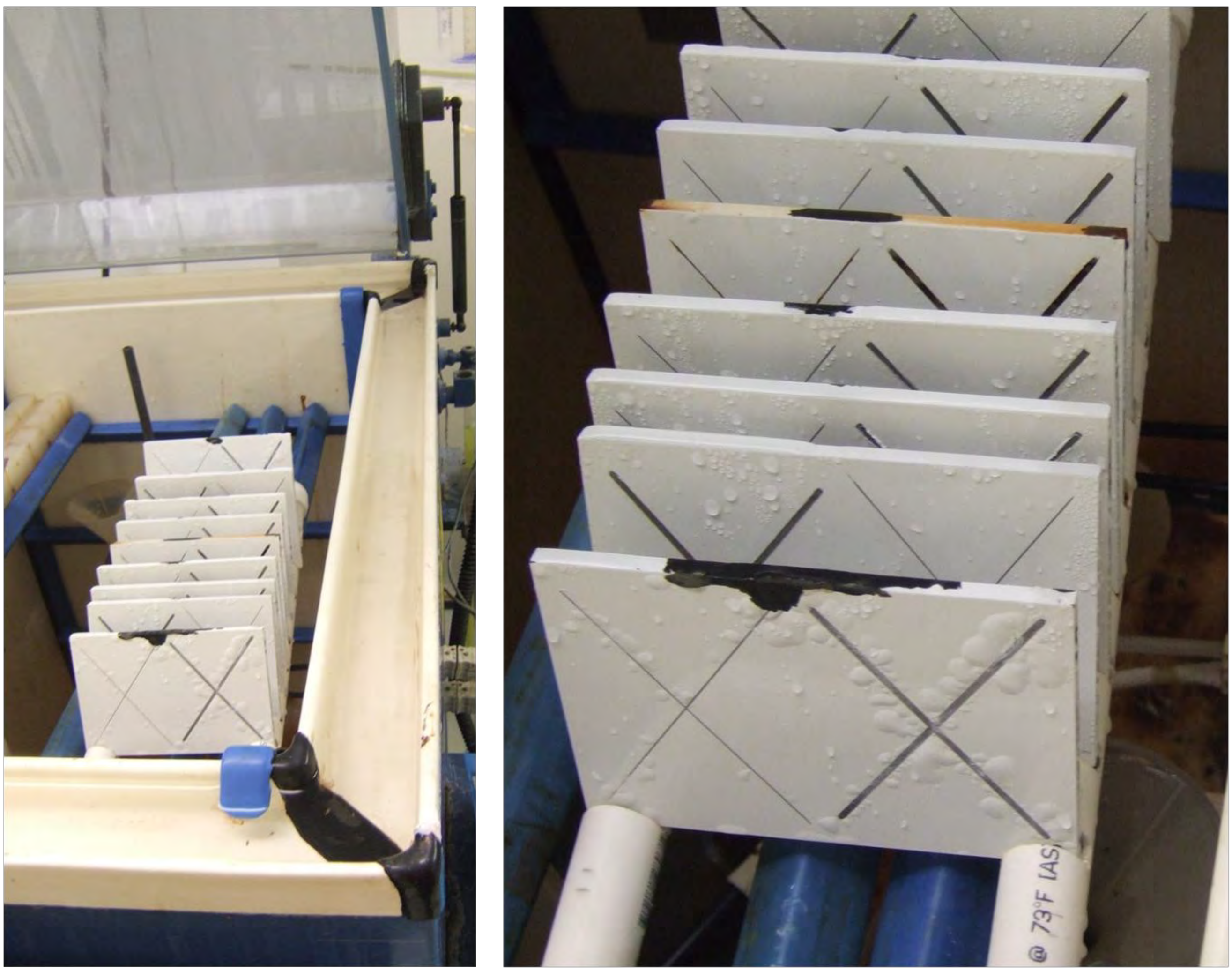

Figure 1 – Test setup shown after completion of 500 hour long test

TABLE 2 TEST PANEL FABRICATION AND PROTECTION SCHEMES

Specification	Prior to Heat Treatment	Condition	Coatings	Test Duration (Hours)	Scribe Width (mm)
UNS G43400 (AMS 6414)	Excise 12 x 107 x 157 mm samples from 150 mm round barstock	Heat treated per AMS 2759/2 1793 - 1931 MPa; ground 32 RMS; stress-relieved at 268°C for 4 hours; nital etch inspected per MIL-STD-867; bakeout at 191°C for 24 hours; shot peened per AMS 2430/2432; grit blasted per MIL-STD 1504	Brush cadmium plate per MIL-STD-865, Class I, Type II; baked for 4 hours at 191°C within 4 hours of plating; primed per MIL-PRF-85582, Type 1, Class C2; Painted (two coats) per MIL-PRF-85285, Type 1, Class W, Color #17925 per Fed-Std-595	100 and 500	0.5 and 2.5
UNS K44220 (AMS 6257)	Excise 12 x 107 x 157 mm samples from 150 mm round barstock	Heat treated per AMS 2759/2 1931 - 2103 MPa; ground 32 RMS; stress-relieved at 268°C for 4 hours; nital etch inspected per MIL-STD-867; bakeout at 191°C for 24 hours; shot peened per AMS 2430/2432; grit blasted per MIL-STD 1504	Cadmium electroplate per MIL-STD-870, Type II, Class 2 chromate conversion coating; primed per MIL-PRF-85582, Type 1, Class C2; Painted (two coats) per MIL-PRF-85285, Type 1, Class W, Color #17925 per Fed-Std-595	100 and 500	0.5 and 2.5
UNS K92580 (AMS 6532)	Excise 12 x 107 x 157 mm samples from 150 mm round barstock	Heat treatment per AMS 2759/2 1931 - 2103 MPa; ground 32 RMS; stress-relieved at 268°C for 4 hours; shot peened per AMS 2430/2432; grit blasted per MIL-STD 1504	Cadmium electroplated per MIL-STD-870, Type II, Class 2 chromate conversion coating; Primed per MIL-PRF-85582, Type 1, Class C2; Painted (two coats) per MIL-PRF-85285, Type 1, Class W, Color #17925 per Fed-Std-595	100 and 500	0.5 and 2.5
UNS K91973 (AMS 6516)	Excise 12 x 107 x 157 mm samples from 190 mm square barstock	Heat treated per AMS 2759 1931 - 2103 MPa(1); ground 32 RMS; stress-relieved at 268°C for 4 hours; shot peened per AMS 2430/2432; grit blasted per MIL-STD 1504	Zinc-Nickel electoplated per AMS 2417, Type 3; Pre-primed per AMS 3175; Primed per MIL-PRF-85582, Type 2, Class C2; Painted (two coats) per MIL-PRF-85285, Type 1, Class W, Color #17925 per Fed-Std-595	100 and 500	0.5 and 2.5
UNS K91973 (AMS 6516)	Excise 12 x 107 x 157 mm samples from 190 mm square barstock	Heat treated per AMS 2759 1931 - 2103 MPa(1); ground 32 RMS; stress-relieved at 268°C for 4 hours; shot peened per AMS 2430/2432; grit blasted per MIL-STD 1504	Cadmium electroplated per MIL-STD-870, Type II, Class 2 chromate conversion coating; Primed per MIL-PRF-85582, Type 1, Class C2; Painted (two coats) per MIL-PRF-85285, Type 1, Class W, Color #17925 per Fed-Std-595	100 and 500	0.5 and 2.5
UNS S10500 (AMS 5922)	Excise 12 x 107 x 157 mm samples from 200 mm round barstock	Heat treated per 2759 1931 - 2103 MPa(2); ground 32 RMS; stress-relieved at 268°C for 4 hours; shot peen per AMS 2430/2432; Passivated per AMS 2700, Method 1, Type 8; baked for 4 hours at 191°C; grit blasted per MIL-STD 1504	Pre-primed per AMS 3175; Primed per MIL-PRF-85582, Type 2, Class C2; Painted (two coats) per MIL-PRF-85285, Type 1, Color #17925 per Fed-Std-595	100 and 500	0.5 and 2.5
UNS S10500 (AMS 5922)	Excise 12 x 107 x 157 mm samples from 200 mm round barstock	Heat treated per 2759 1931 - 2103 MPa(2); ground 32 RMS; stress-relieved at 268°C for 4 hours; shot peen per AMS 2430/2432; Passivated per AMS 2700, Method 1, Type 8; baked for 4 hours at 191°C; grit blasted per MIL-STD 1504	Zinc-Nickel electoplated per AMS 2417, Type 3; Pre-primed per AMS 3175; Primed per MIL-PRF-85582, Type 2, Class C2; Painted (two coats) per MIL-PRF-85285, Type 1, Class W, Color #17925 per Fed-Std-595	100 and 500	0.5 and 2.5
UNS S10500 (AMS 5922)	Excise 12 x 107 x 157 mm samples from 200 mm round barstock	Heat treated per 2759 1931 - 2103 MPa(2); ground 32 RMS; stress-relieved at 268°C for 4 hours; shot peen per AMS 2430/2432; Passivated per AMS 2700, Method 1, Type 8; baked for 4 hours at 191°C; grit blasted per MIL-STD 1504	Cadmium electroplated per MIL-STD-870, Type II, Class 2 chromate conversion coating; Primed per MIL-PRF-85582, Type 1, Class C2; Painted (two coats) per MIL-PRF-85285, Type 1, Class W, Color #17925 per Fed-Std-595	100 and 500	0.5 and 2.5
UNS S15500 (AMS 5659)	25 x 400 mm barstock	Heat treated per 2759/3 1310 MPa; ground 32 RMS; stress-relieved at 268°C for 4 hours; shot peen per AMS 2430/2432; Passivated per AMS 2700, Method 1, Type 8; baked for 4 hours at 191°C; grit blasted per MIL-STD 1504	Pre-primed per AMS 3175; Primed per MIL-PRF-85582, Type 2, Class C2; Painted (two coats) per MIL-PRF-85285, Type 1, Color #17925 per Fed-Std-595	500	0.5 and 2.5

(1) 1060°C 1 hour, oil quenched, -73°C 1 hour, air warmed, 525°C 6 hours, air cooled
(2) 1085°C 1 hour, oil quenched, -73°C 1 hour, air warmed, 501°C 3 hours, water quenched, -73°C 1 hour, air warmed, 482°C 12 hours, air cooled

RESULTS

A summary of results for all test panels is presented in TABLE 3. The rating for the amount of rust present was based on ASTM D610 (Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces). This standard was applied to the scribed areas only and not to the panel as a whole. Therefore, if there was rust present within the scribe, a rating was assigned; if no rust was present within the scribe, a rating of “none” was provided. The rating for the amount of blistering present was based on ASTM D714 (Standard Test Method for Evaluating Degree of Blistering of Paints). This standard was applied to the area along the scribe only as blistering did not occur in other locations. If no blistering was present, a rating of “none” was provided.

The summary of results is followed by a description of the test panels and representative images in separate sections based on duration of test. Each alloy and its respective protection scheme are presented as a group. Photographs of the as-scribed and post test condition are presented next to each other to provide a visual comparison. These photos are followed by a SEM image of the intersection of the 2.5 mm scribe and a representative location within the scribe at a distance away from the intersection. Lastly, a SEM image of the intersection of the 0.5 mm scribe and a representative location within the scribe at a distance away from the intersection is presented. The SEM images provide descriptions of any base metal present, corrosion product formed, presence of oxides, and any indications of blistering or undercutting of the protection scheme.

TABLE 3 – TEST PANEL EVALUATION AND RATINGS FOR DEGREE OF RUSTING AND DEGREE OF BLISTERING

Specification	Protection Scheme	Test Duration (hours)	Scribe Width (mm)	Degree of Rusting (ASTM D610)	Degree of Blistering (ASTM D714)	Comment
UNS G43400 (AMS 6414)	cadmium + chromate + primer + paint	100	0.5	none	none	1
			2.5	6-G	No. 8, few	1,2,5
		500	0.5	9-G	No. 4, few	1,2,5
			2.5	3-G	No. 2, dense	1,2,6
UNS K44220 (AMS 6257)	cadmium + chromate + primer + paint	100	0.5	9-P	none	1,3
			2.5	9-P	No. 6, medium-dense	1,3,6
		500	0.5	9-P	No. 8, few	1,3,5
			2.5	5-P	No. 2, dense	1,3,6,7
UNS K92580 (AMS 6532)	cadmium + chromate + primer + paint	100	0.5	none	none	1
			2.5	none	none	1
		500	0.5	none	none	1
			2.5	none	No. 2, medium	1,5
UNS K91973 (AMS 6516)	zinc-nickel + phosphate + primer + paint	100	0.5	none	No. 6, very few	4,5
			2.5	none	No. 2, medium	4,5
		500	0.5	none	No. 2, medium-dense	4,6
			2.5	none	No. 2, dense	4,6
UNS K91973 (AMS 6516)	cadmium + chromate + primer + paint	100	0.5	none	none	1
			2.5	none	No. 4, very few	1,5
		500	0.5	none	No. 8, very few	1,5
			2.5	none	No. 4, few	1,5
UNS S10500 (AMS 5922)	boegel + primer + paint	100	0.5	6-P	none	3
			2.5	7-P	none	3
		500	0.5	7-P	No. 8, medium	3,5
			2.5	6-P	No. 4, few	3,5,7
UNS S10500 (AMS 5922)	zinc-nickel + phosphate + primer + paint	100	0.5	none	No. 6, few	4,5
			2.5	none	No. 2, medium	4,5
		500	0.5	none	No. 2, medium	4,5
			2.5	none	No. 2, medium-dense	4,6
UNS S10500 (AMS 5922)	cadmium + chromate + primer + paint	100	0.5	none	none	1
			2.5	none	none	1
		500	0.5	none	none	1
			2.5	none	No. 4, few	1,5
UNS S15500 (AMS 5659)	boegel + primer + paint	500	0.5	none	none	
			2.5	9-P	none	3

(1) Presence of cadmium oxide within the scribe indicates initial breakdown of sacrifical coating
(2) Iron-oxide corrosion product present in the form of general corrosion
(3) Iron-oxide corrosion product present in the form of pin hole corrosion
(4) Presence of zinc-nickel oxide within the scribe indicates initial breakdown of sacrificial coating
(5) Minor blistering starting to form along length of scribe
(6) Blistering present along length of scribe
(7) Some undercutting near scribe intersection

100 hour test

UNS G43400 (cadmium + chromate + primer + paint). The UNS G43400 test panel with the cadmium, chromate, primer, and paint protection scheme exhibited a few minor blisters on only the 2.5 mm scribe, as seen in Figure 2. Figure 3 indicates regions on the 2.5 mm scribe intersection that are either base metal or cadmium oxide, while the scribe line away from the intersection exhibits areas of red rust in addition to the base metal and cadmium oxide. The 0.5 mm scribe intersection and scribe line both have cadmium oxide present on the base metal, but no rust is present, as seen in Figure 4.

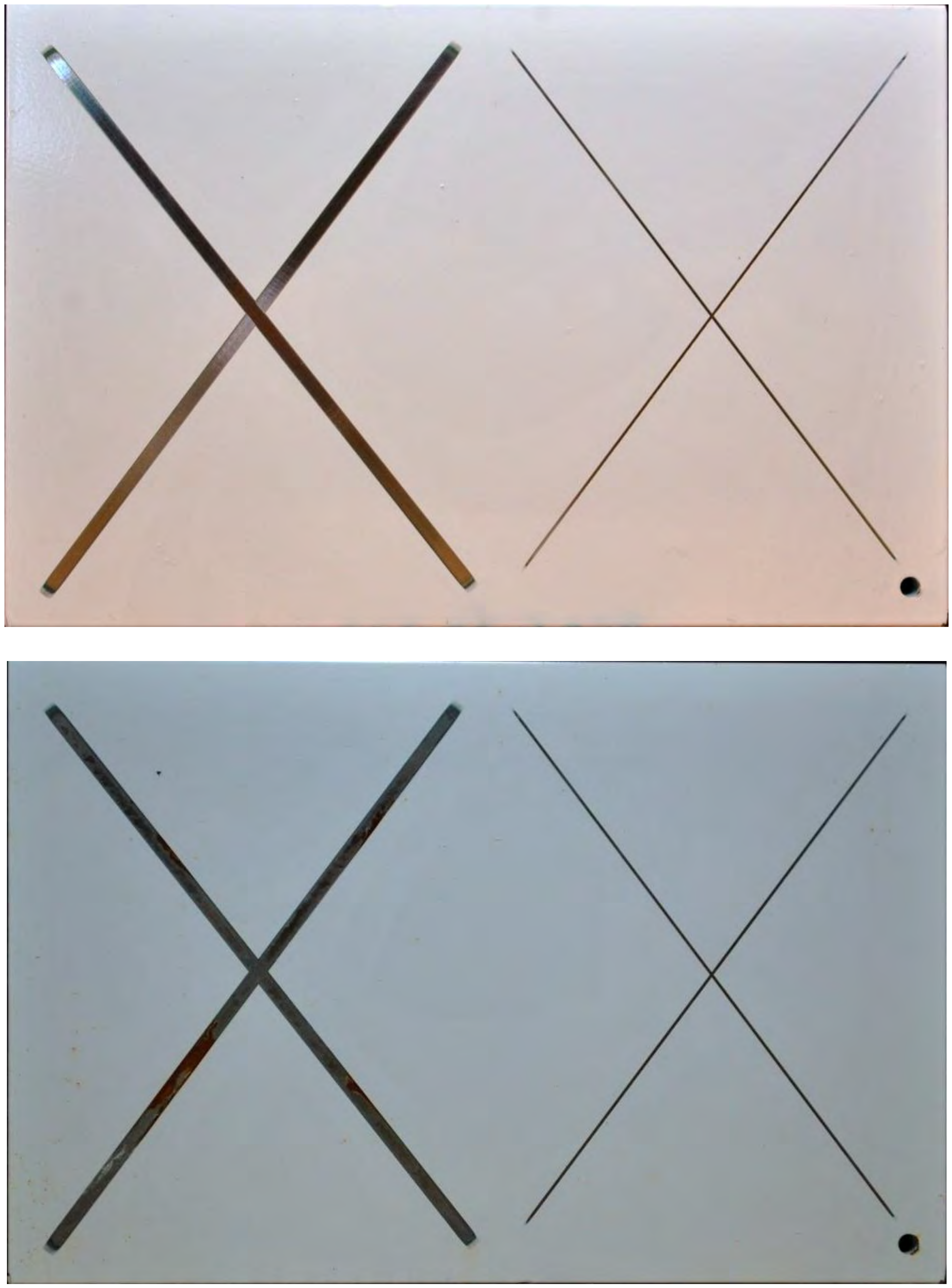

FIGURE 2 – UNS G43400 test panel with cadmium, chromate, primer, and paint protection scheme prior to test (top) and after 100 hour test (bottom) per ASTM B117. Iron oxide corrosion product and small blisters were present on or along the 2.5 mm scribe.

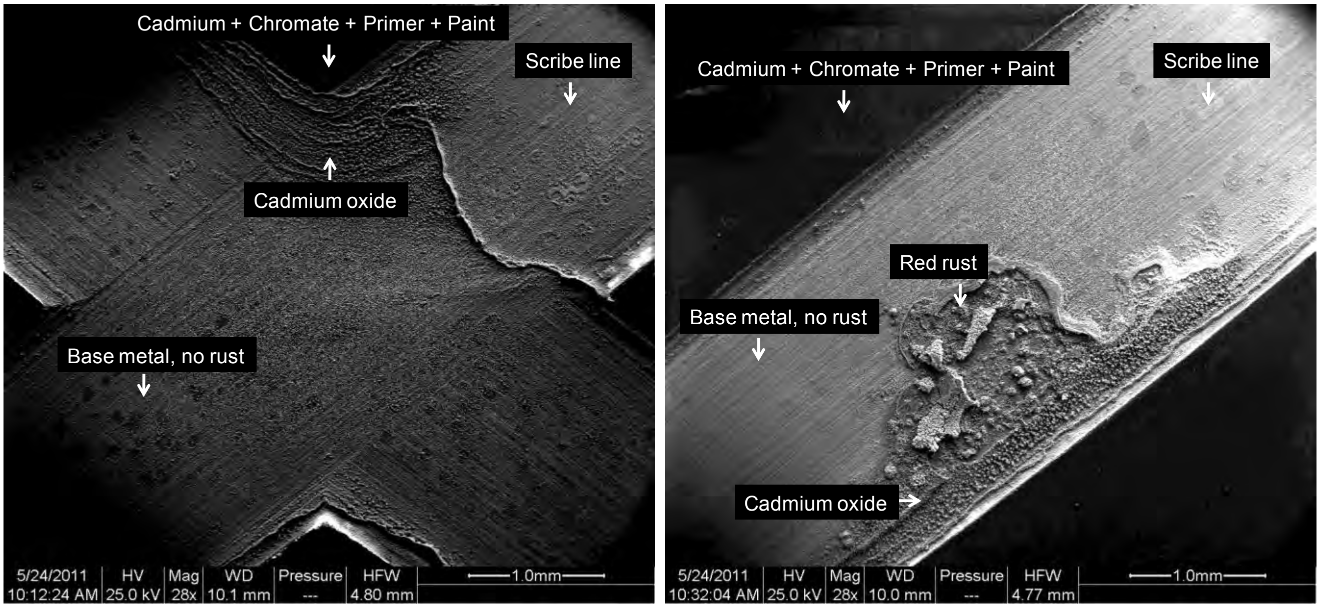

FIGURE 3 – SEM micrograph of UNS G43400 2.5 mm scribe after 100 hour test per ASTM B117. No undercutting of the protection scheme was observed during the analysis. Although not visible in the SEM micrograph, a few minor blisters were present. There was iron oxide corrosion product contained within the length of the scribe.

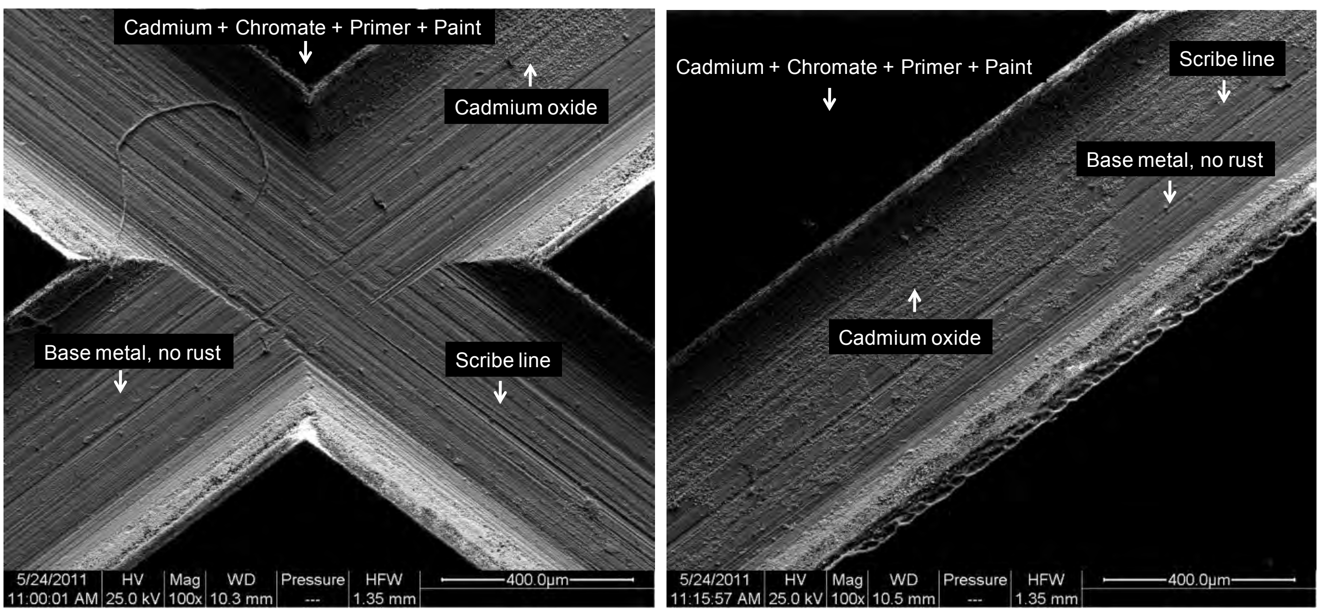

FIGURE 4 – SEM micrograph of UNS G43400 0.5 mm scribe after 100 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis.

UNS K44220 (cadmium + chromate + primer + paint). The UNS K44220 test panel with the cadmium, chromate, primer, and paint protection scheme displayed no undercutting of the paint on either of the scribe widths, although blistering was present along the 2.5 mm scribe, shown in Figure 5. Figure 6 shows regions in the 2.5 mm scribe intersection and along the scribe line that are either base metal, cadmium oxide, or localized iron oxide corrosion product. Figure 7 shows the presence of only base metal and cadmium oxide in the intersection, though rust is present as well further along the scribe line.

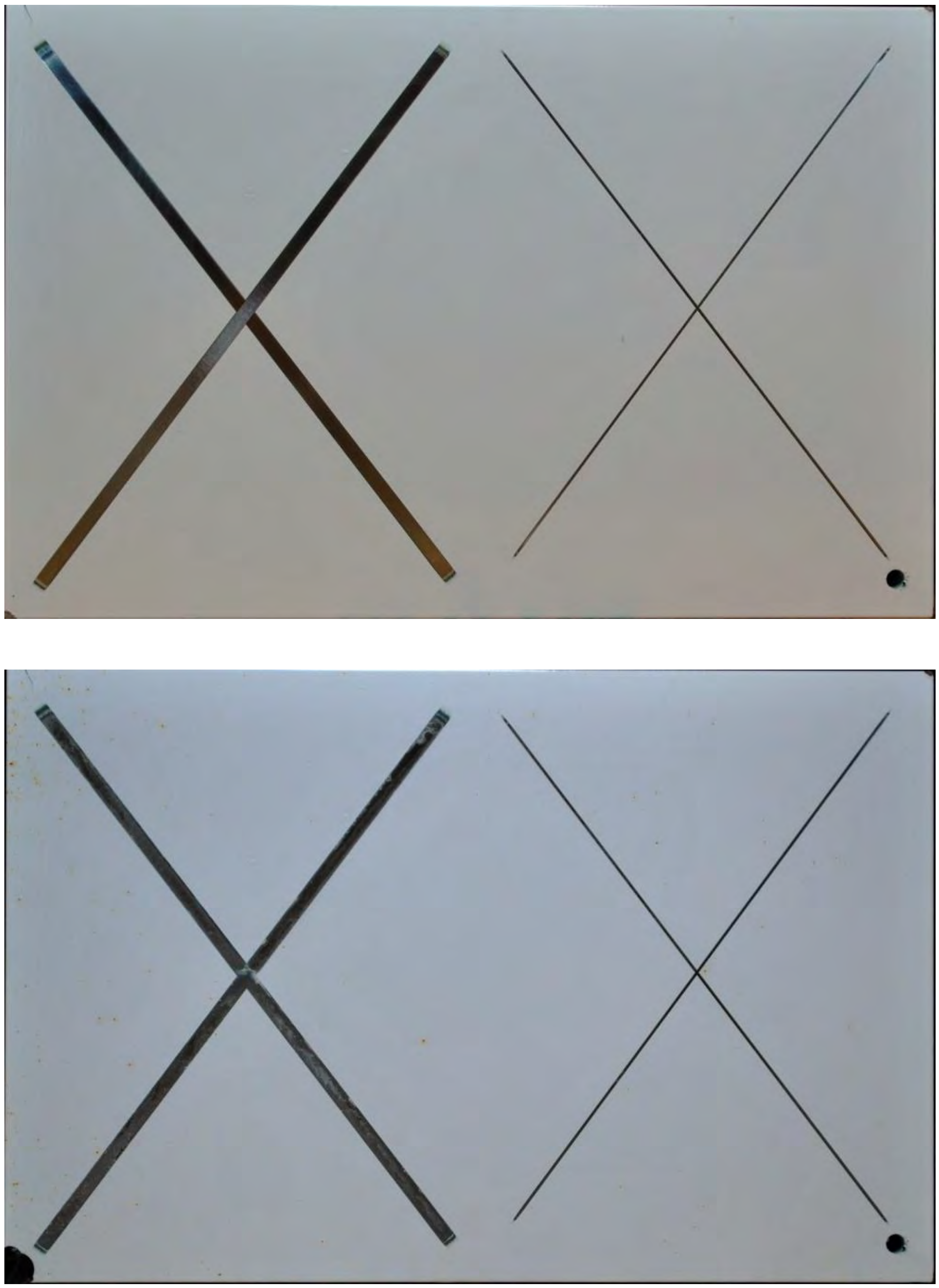

FIGURE 5 – UNS K44220 test panel with cadmium, chromate, primer, and paint protection scheme prior to test (top) and after 100 hour test (bottom) per ASTM B117. Small blisters were present along the 2.5 mm scribe line. Iron oxide corrosion product was present on both scribes.

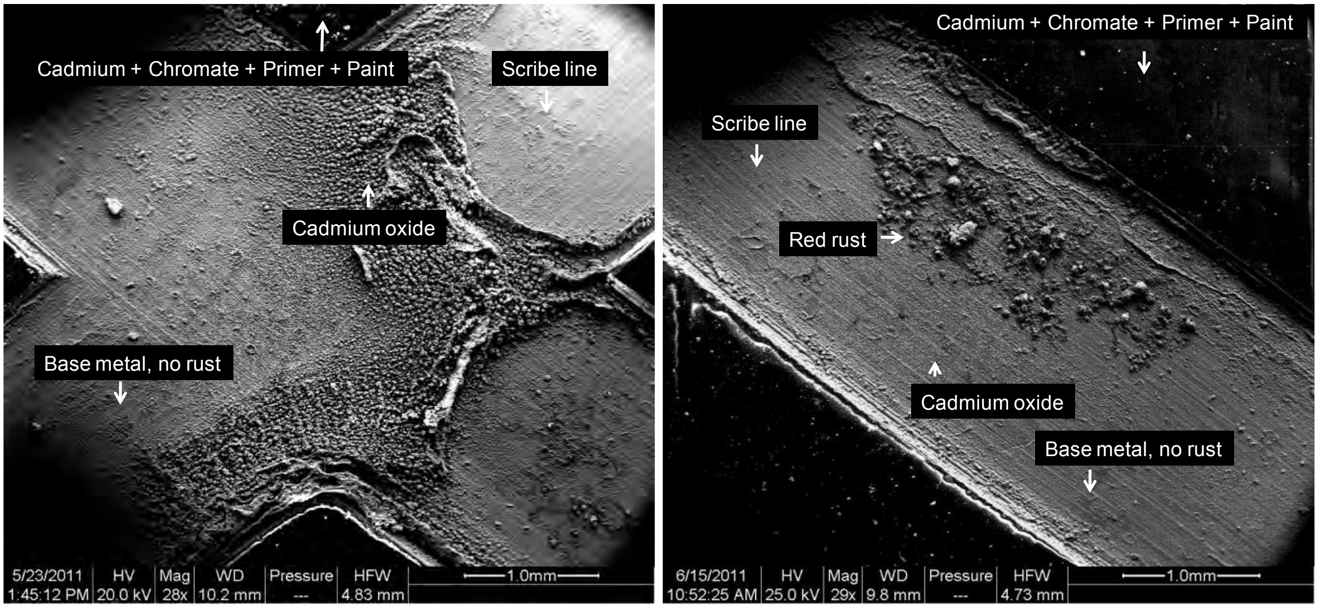

FIGURE 6 – SEM micrograph of UNS K44220 2.5 mm scribe after 100 hour test per ASTM B117. No undercutting of the protection scheme was observed during the analysis. Localized iron oxide corrosion product was present within the length of the scribe.

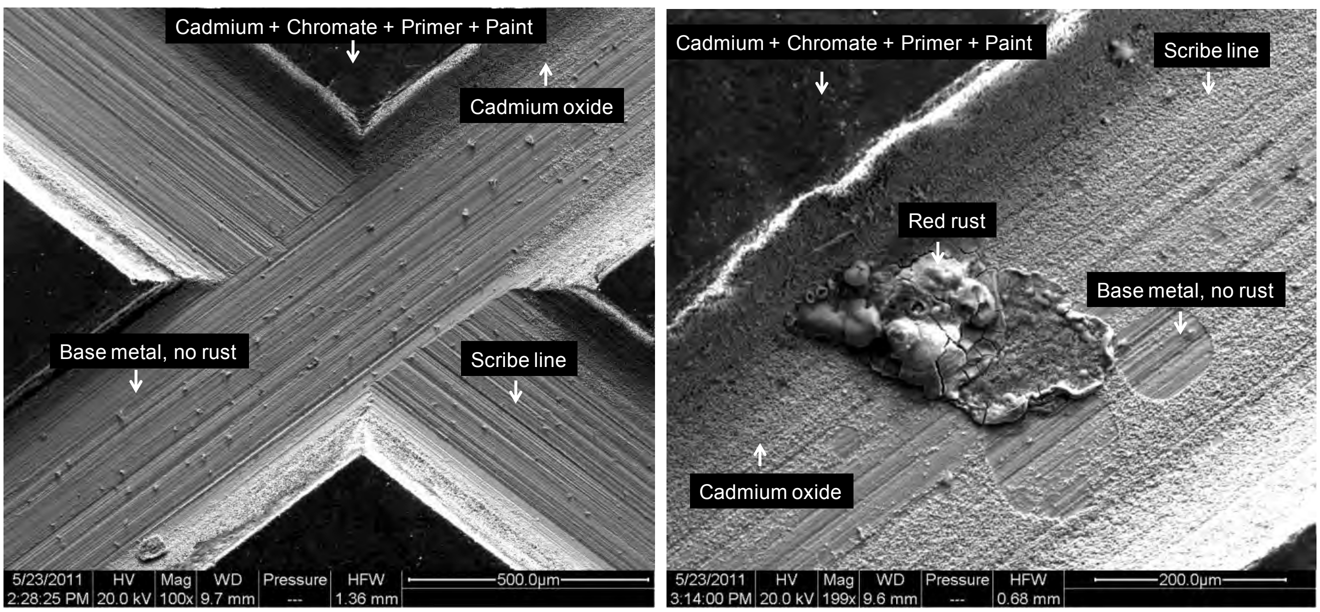

FIGURE 7 – SEM micrograph of UNS K44220 0.5 mm scribe after 100 hour test per ASTM B117. No undercutting of the protection scheme was observed during the analysis. There was localized iron oxide corrosion product contained within the length of the scribe.

UNS K92580 (cadmium + chromate + primer + paint). The UNS K92580 panel with the cadmium, chromate, primer, and paint protection scheme (Figure 8) showed no undercutting or blistering around either of the scribes. Figures 9 and 10 indicate that only base metal and cadmium oxide are present in both the intersection and along the scribe line for the 2.5 mm and 0.5 mm scribe widths, respectively.

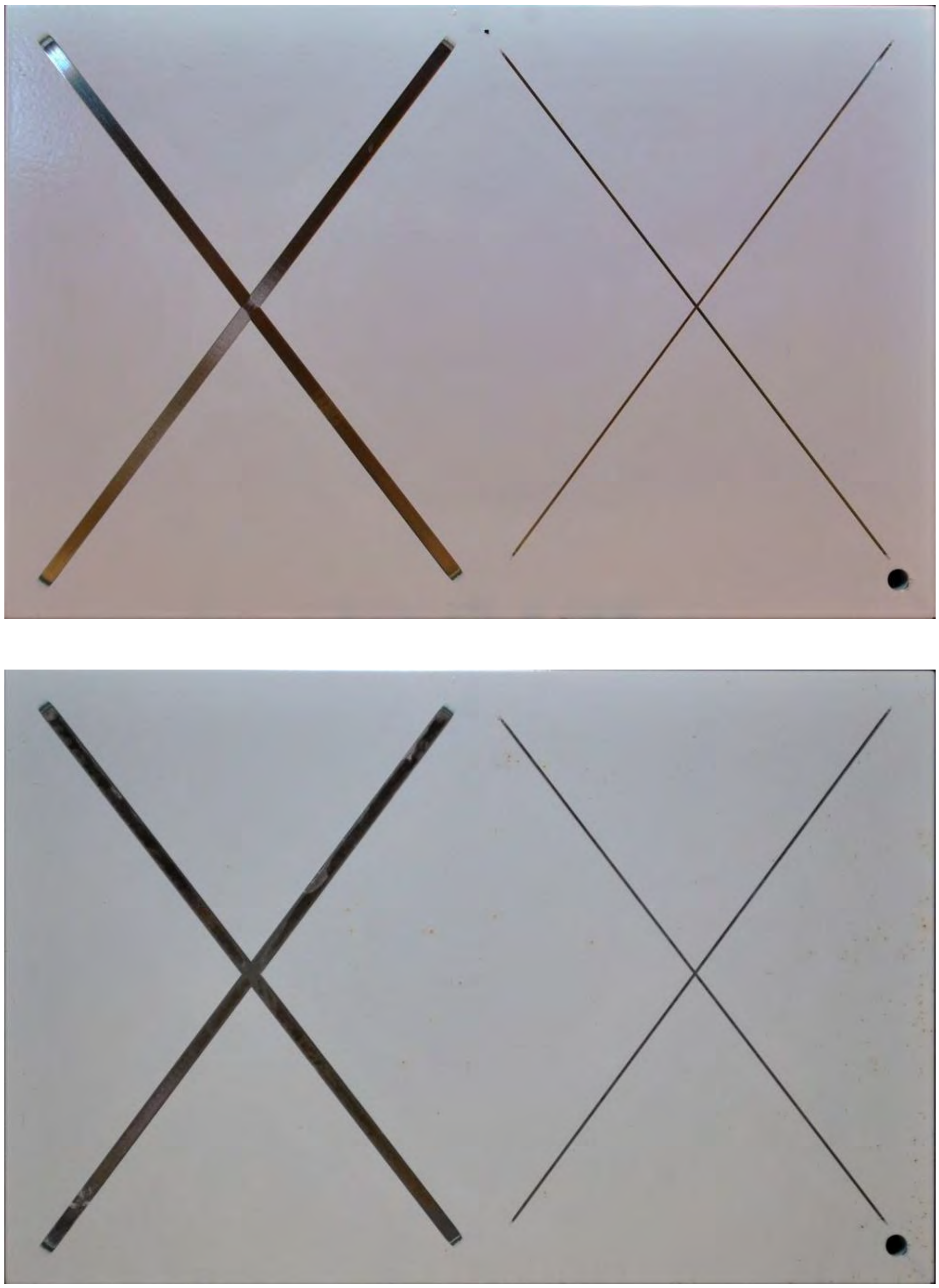

FIGURE 8 – UNS K92580 test panel with cadmium, chromate, primer, and paint protection scheme prior to test (top) and after 100 hour test (bottom) per ASTM B117. No undercutting of the protection scheme was observed.

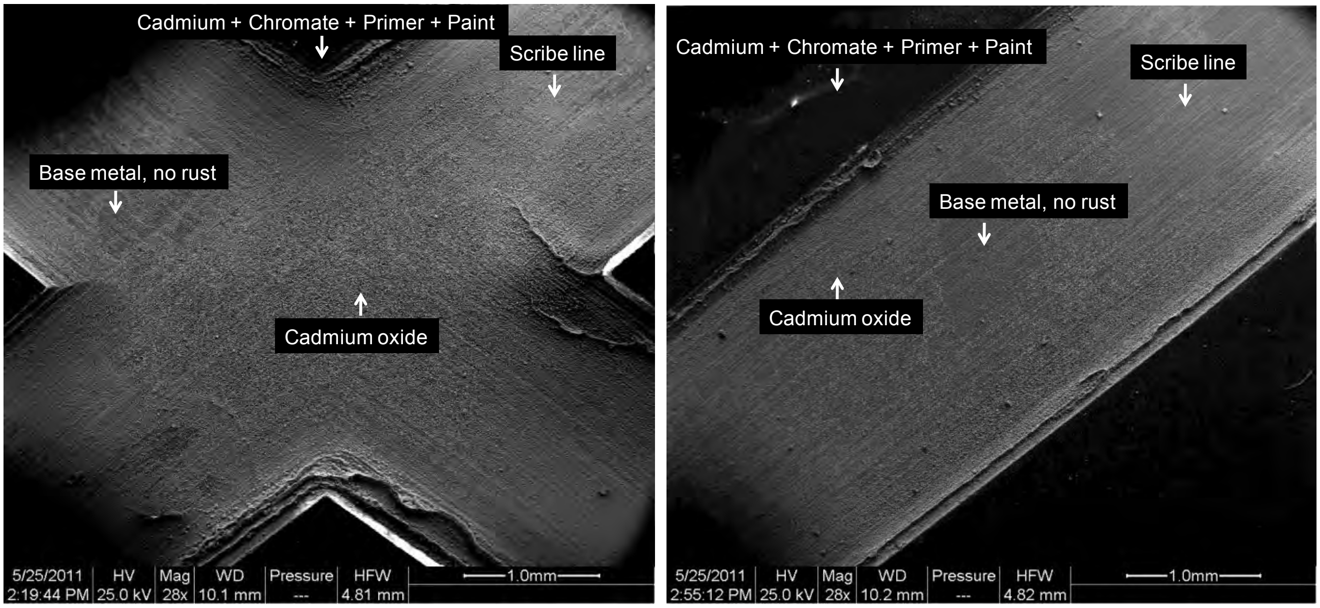

FIGURE 9 – SEM micrograph of UNS K92580 2.5 mm scribe after 100 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis.

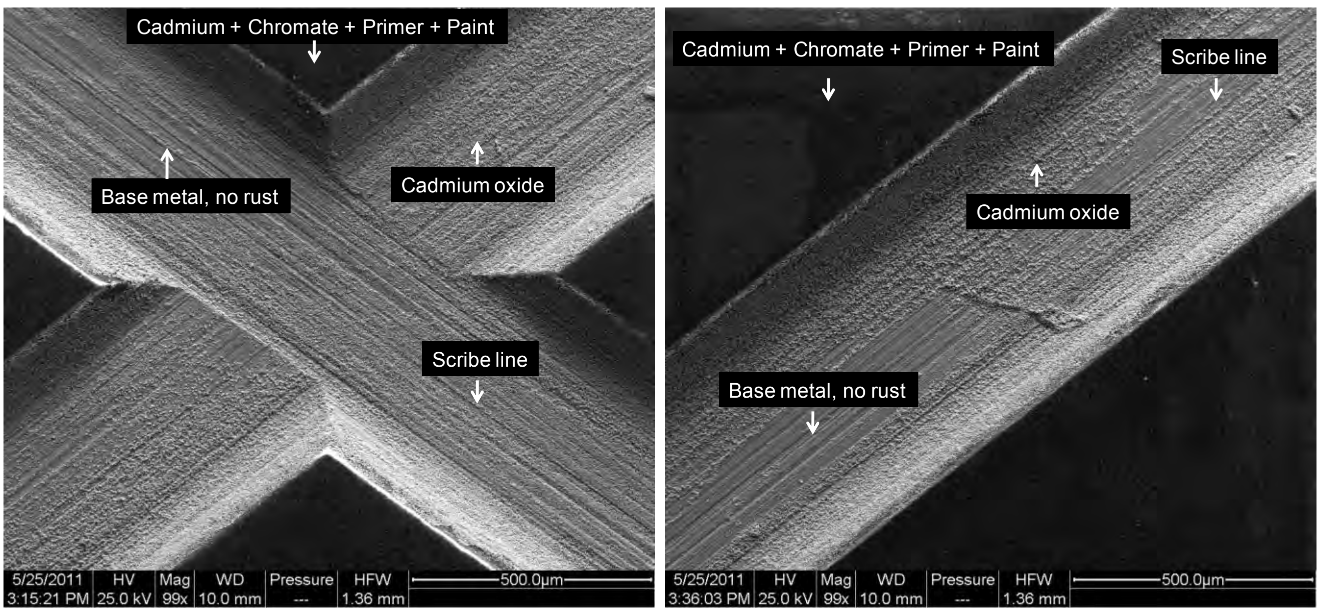

FIGURE 10 – SEM micrograph of UNS K92580 0.5 mm scribe after 100 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis.

UNS K91973 (zinc-nickel + phosphate + pre-primer + primer + paint). The UNS K91973 panel with the zinc-nickel, phosphate, pre-primer, primer, and paint protection scheme exhibited some blistering along the 2.5 mm scribe lines and a few minor blisters along the 0.5 mm scribe lines, as seen in Figure 11. Figure 12 shows regions of zinc-nickel oxide and base metal in the 2.5 mm scribe intersection and along the scribe line. Zinc-nickel oxide and based metal were also the only constituents present in the 0.5 mm scribe intersection and along the scribe line, as seen in Figure 13.

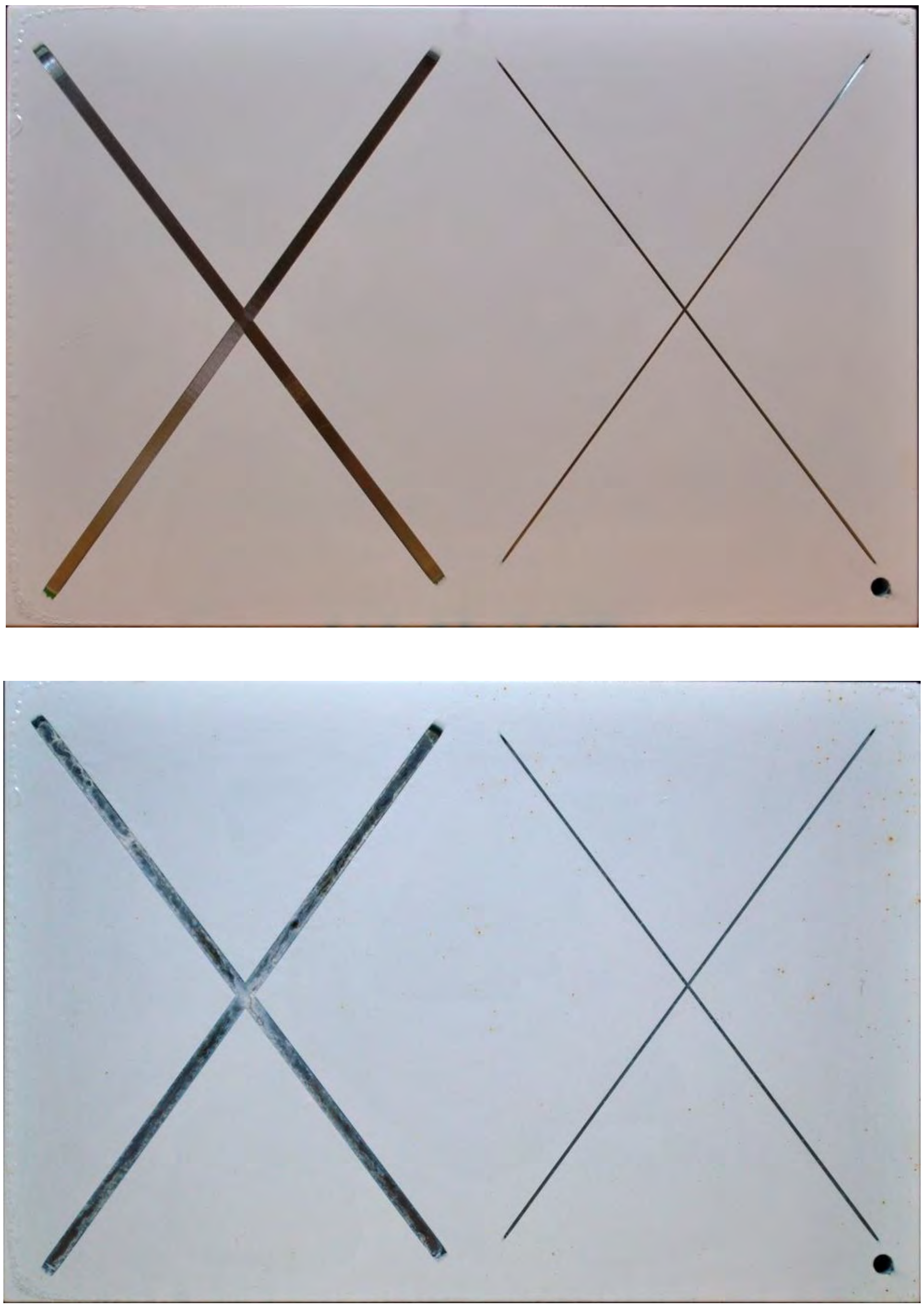

Figure 11 - UNS K91973 test panel with zinc-nickel, phosphate, pre-primer, primer, and paint protection scheme prior to test (top) and after 100 hour test (bottom) per ASTM B117. Some blistering of the paint is observed near the scribes.

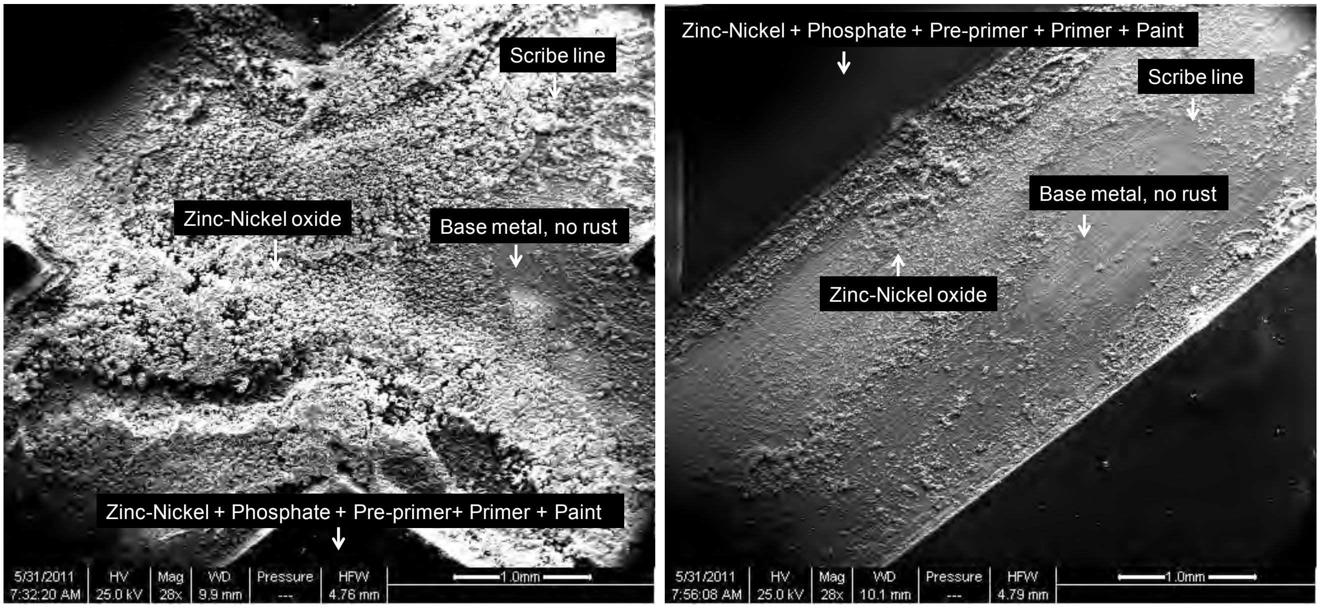

FIGURE 12 - SEM micrograph of UNS K91973 2.5 mm scribe after 100 hour test per ASTM B117. Blistering of the protection scheme can be seen along scribe lines, although not shown in SEM image.

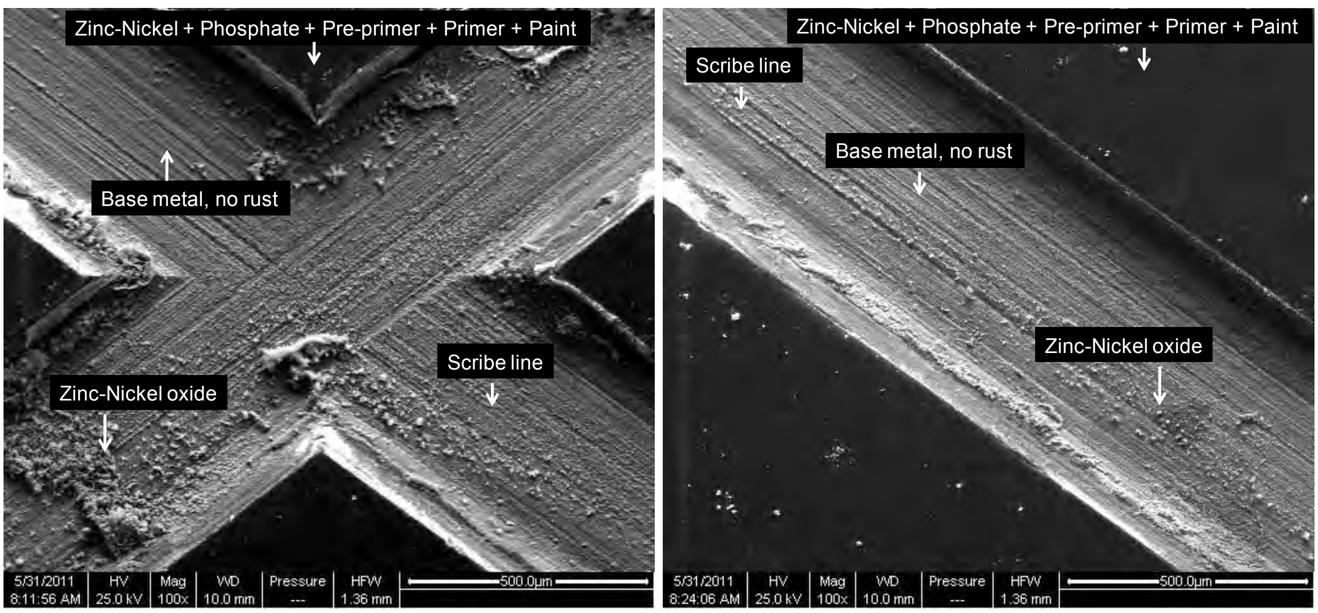

FIGURE 13 - SEM micrograph of UNS K91973 0.5 mm scribe after 100 hour test per ASTM B117. Minor blistering of the protection scheme can be seen along scribe lines, although not shown in SEM image.

<u>UNS K91973 (cadmium + chromate + primer + paint)</u>. The UNS K91973 panel with the cadmium, chromate, primer, and paint protection scheme produced a few minor blisters along the 2.5 mm scribe (Figure 14). Figure 15 shows cadmium oxide and base metal are present on the 2.5 mm scribe intersection and further down one of the scribes. Similarly, cadmium oxide and base metal regions were present along the 0.5 mm scribe intersection and scribe line (Figure 16), although pieces of residual salt not rinsed away from the panels can also be seen in the intersection.

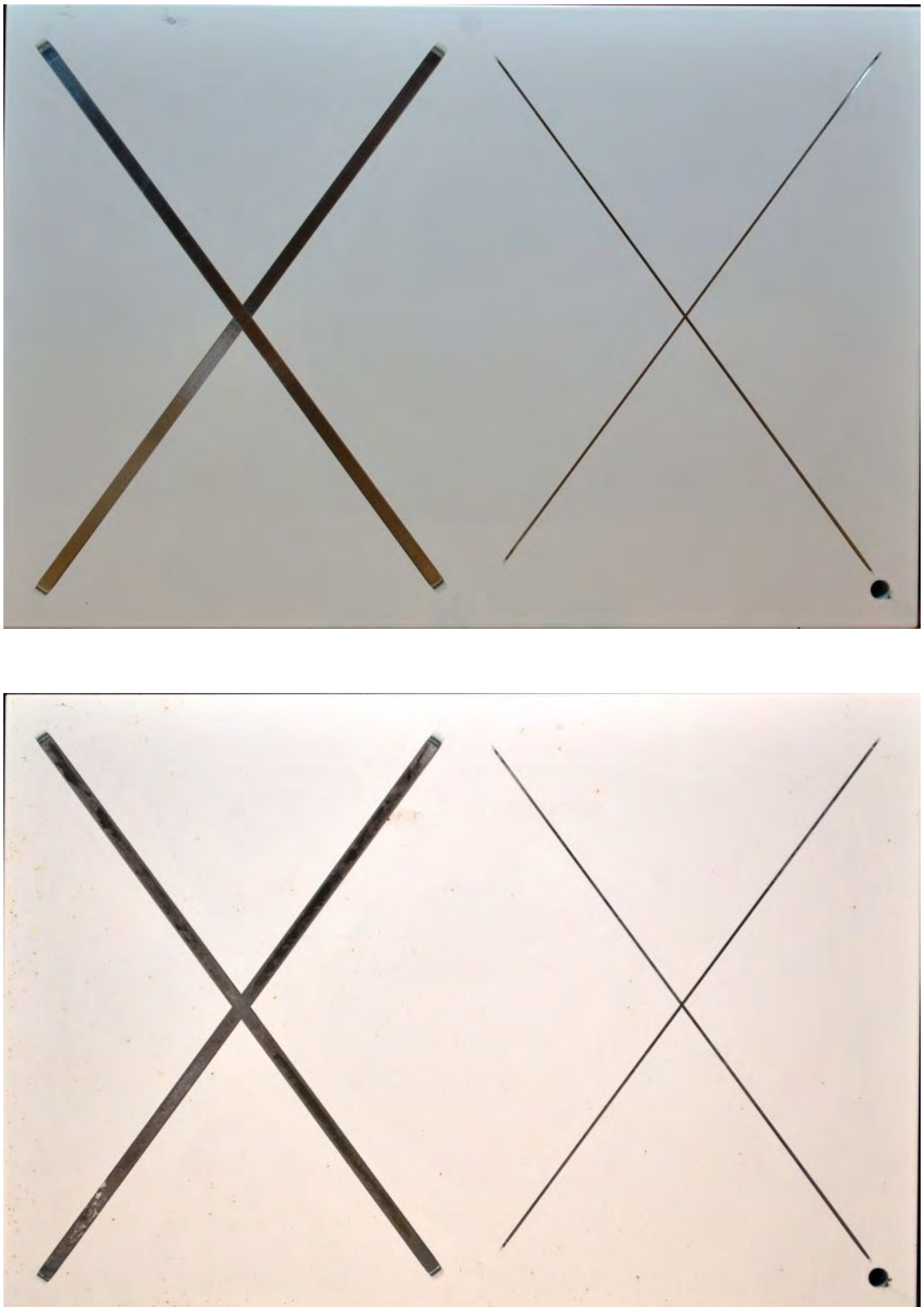

FIGURE 14 – UNS K91973 test panel with cadmium, chromate, primer, and paint protection scheme prior to test (top) and after 100 hour test (bottom) per ASTM B117. A few minor blisters were observed along the 2.5 mm scribe line.

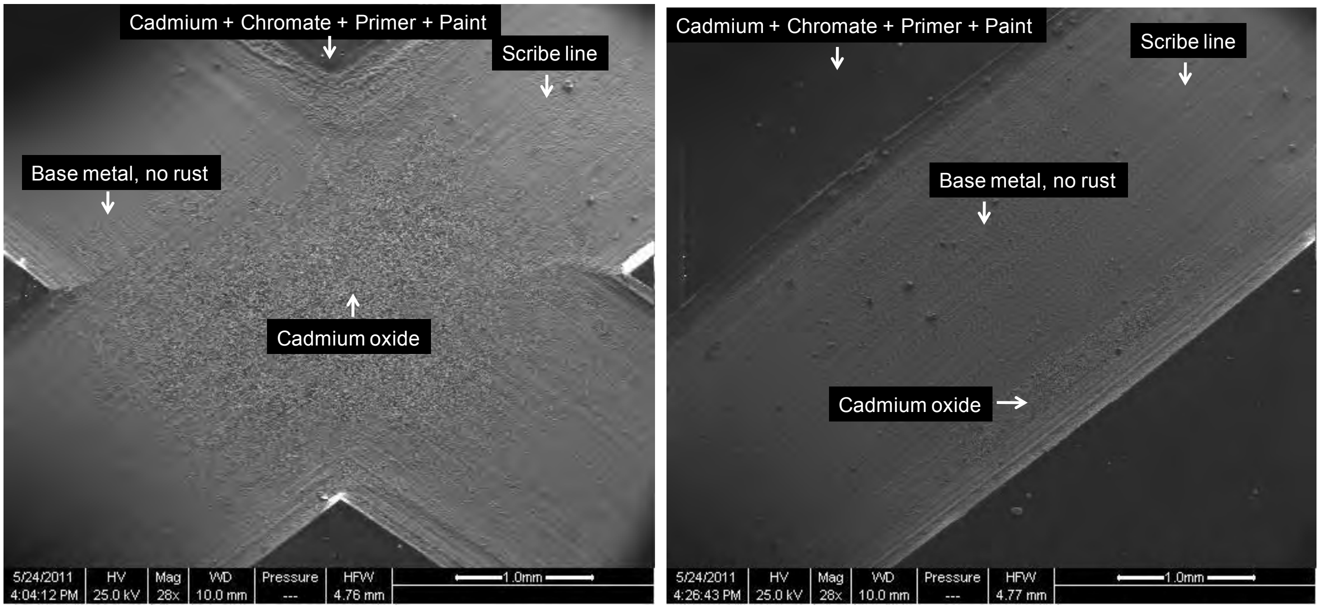

FIGURE 15 – SEM micrograph of UNS K91973 2.5 mm scribe after 100 hour test per ASTM B117. A few minor blisters were present along the scribe line. No undercutting of the protection scheme was observed during the analysis.

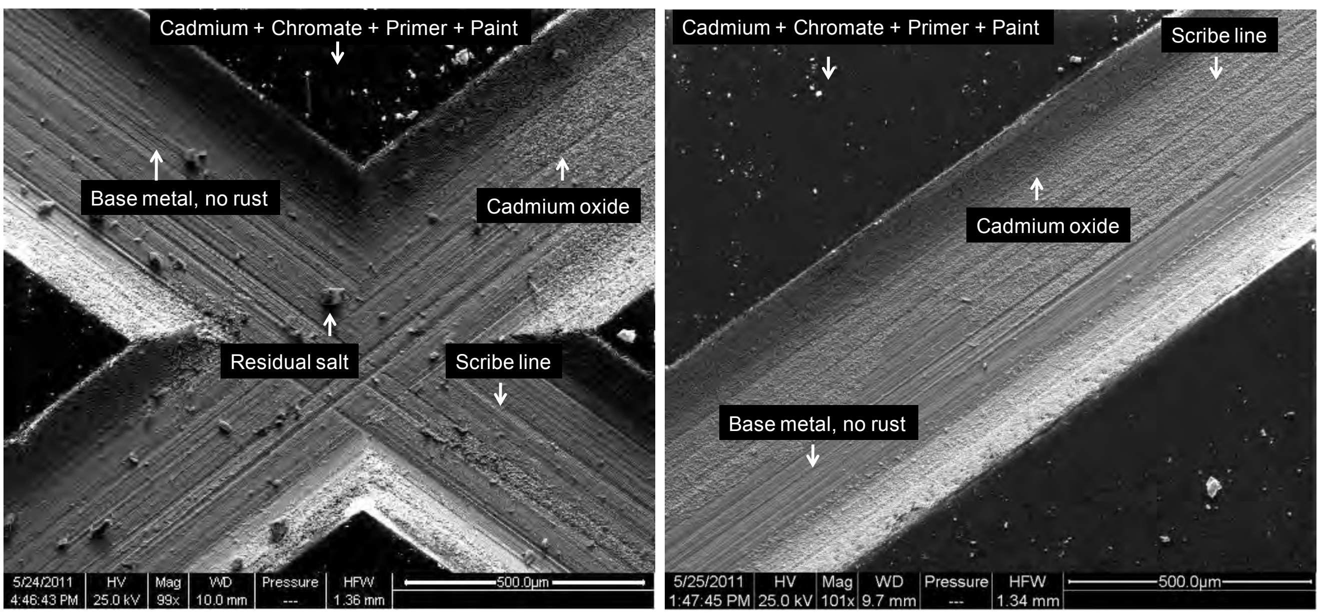

FIGURE 16 – SEM micrograph of UNS K91973 0.5 mm scribe after 100 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis.

UNS S10500 (pre-primer + primer + paint). The UNS S10500 panel with the pre-primer, primer, and paint panel did not display any undercutting or blistering along the scribes, as shown in Figure 17. Base metal and localized iron oxide corrosion product were present both in the intersection and along the scribe line for the 2.5 mm scribe (Figure 18). Localized iron oxide corrosion product and base metal were also present in the intersection and along the scribe of the 0.5 mm scribe, as well as some residual salt (shown in Figure 19).

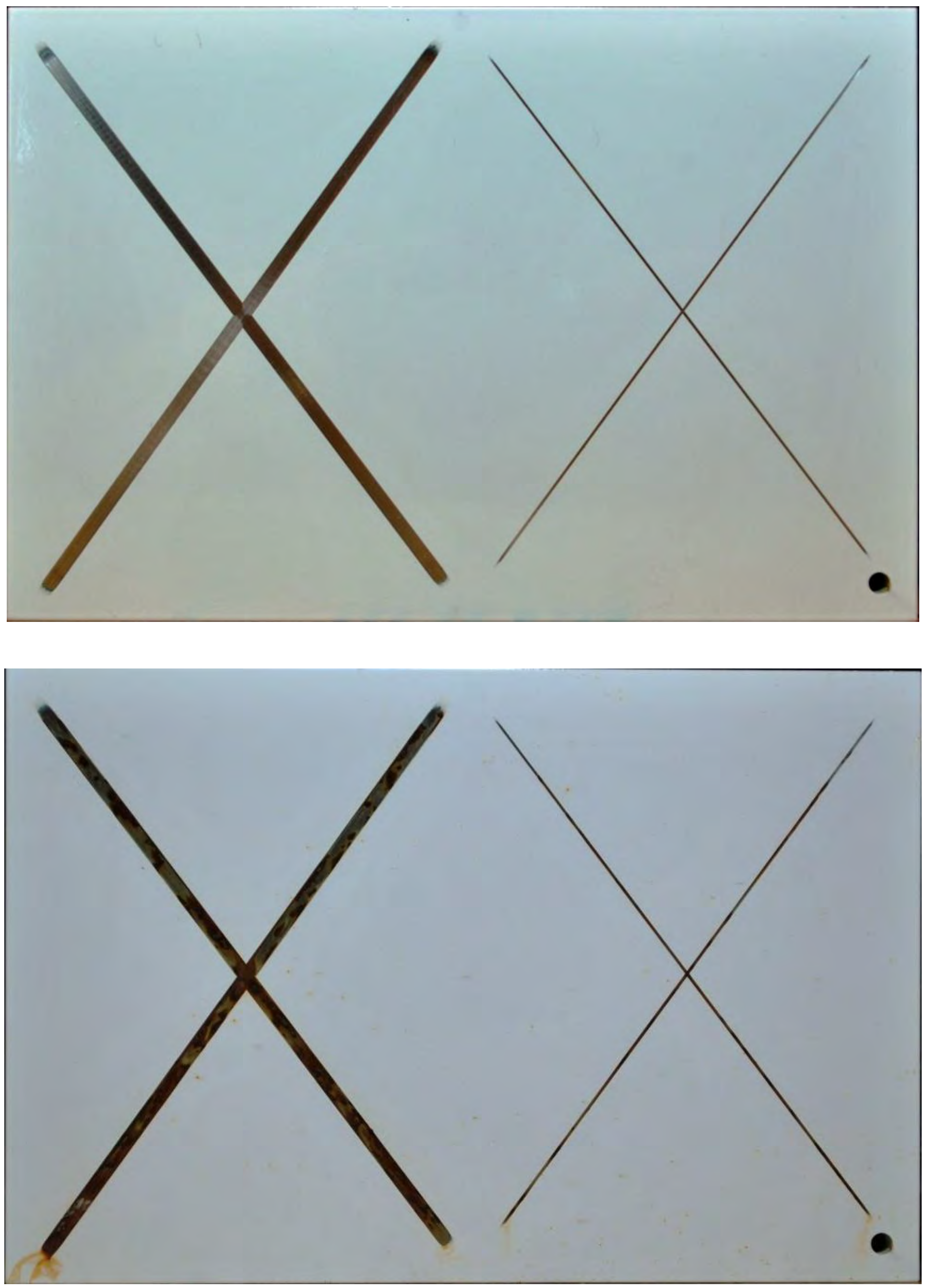

FIGURE 17 – UNS S10500 test panel with pre-primer, primer, and paint protection scheme prior to test (top) and after 100 hour test (bottom) per ASTM B117. While the appearance of iron oxide corrosion product was present, there was no blistering or undercutting of the protection scheme.

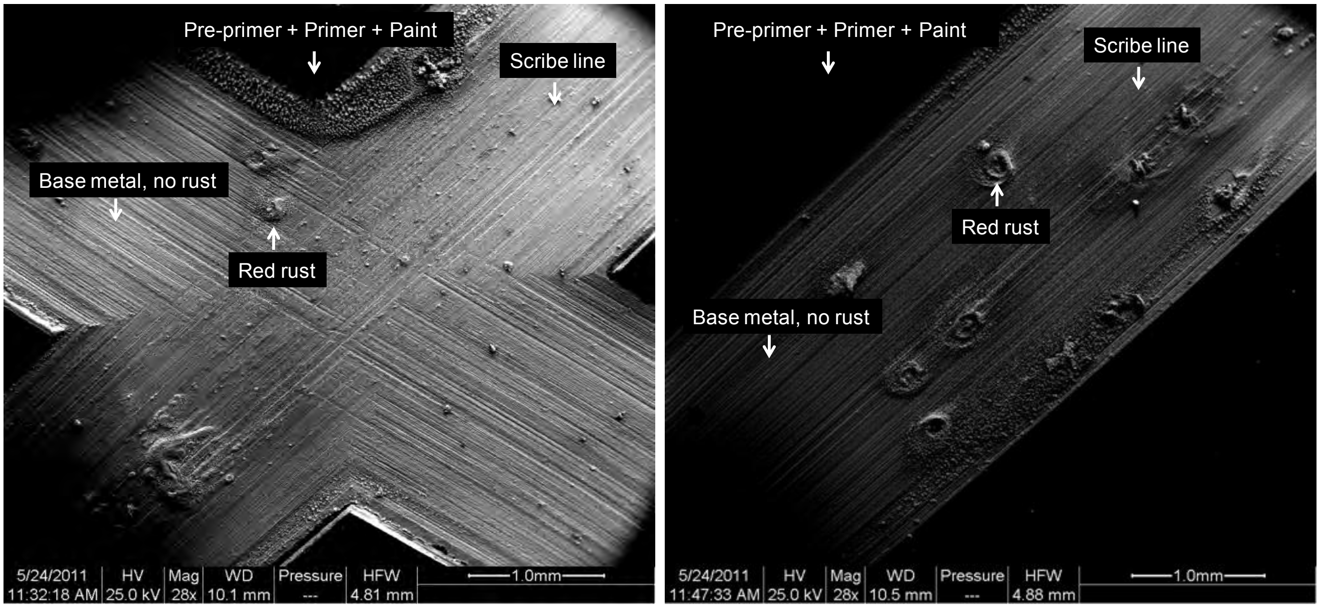

FIGURE 18 – SEM micrograph of UNS S10500 2.5 mm scribe after 100 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis. There was localized iron oxide corrosion product contained within the length of the scribe.

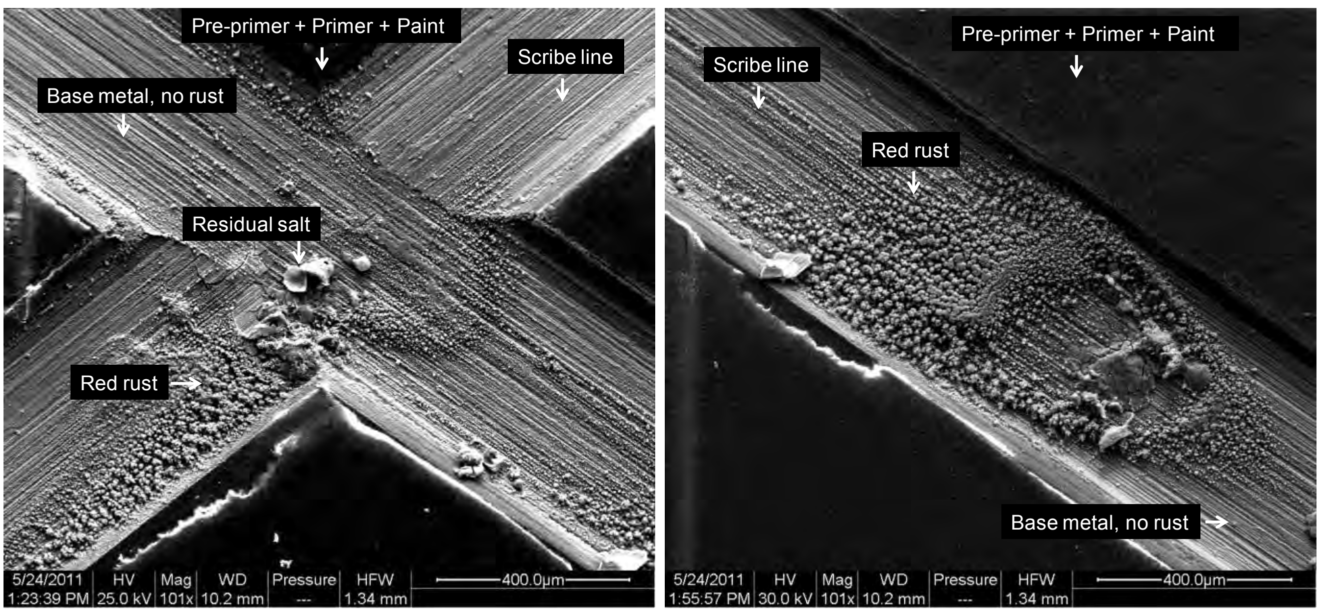

FIGURE 19 – SEM micrograph of UNS S10500 0.5 mm scribe after 100 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis. There was localized iron oxide corrosion product contained within the length of the scribe.

UNS S10500 (zinc-nickel + phosphate + pre-primer + primer + paint). The UNS S10500 panel with the zinc-nickel, phosphate, pre-primer, primer, and paint protection scheme exhibited some blistering along the 2.5 mm scribe lines and a few minor blisters along the 0.5 mm scribe lines, as shown in Figure 20. Figures 21 and 22 indicate zinc-nickel oxide as well as bare metal regions in the intersections and along the scribe lines of the 2.5 mm and 0.5 mm scribes, respectively.

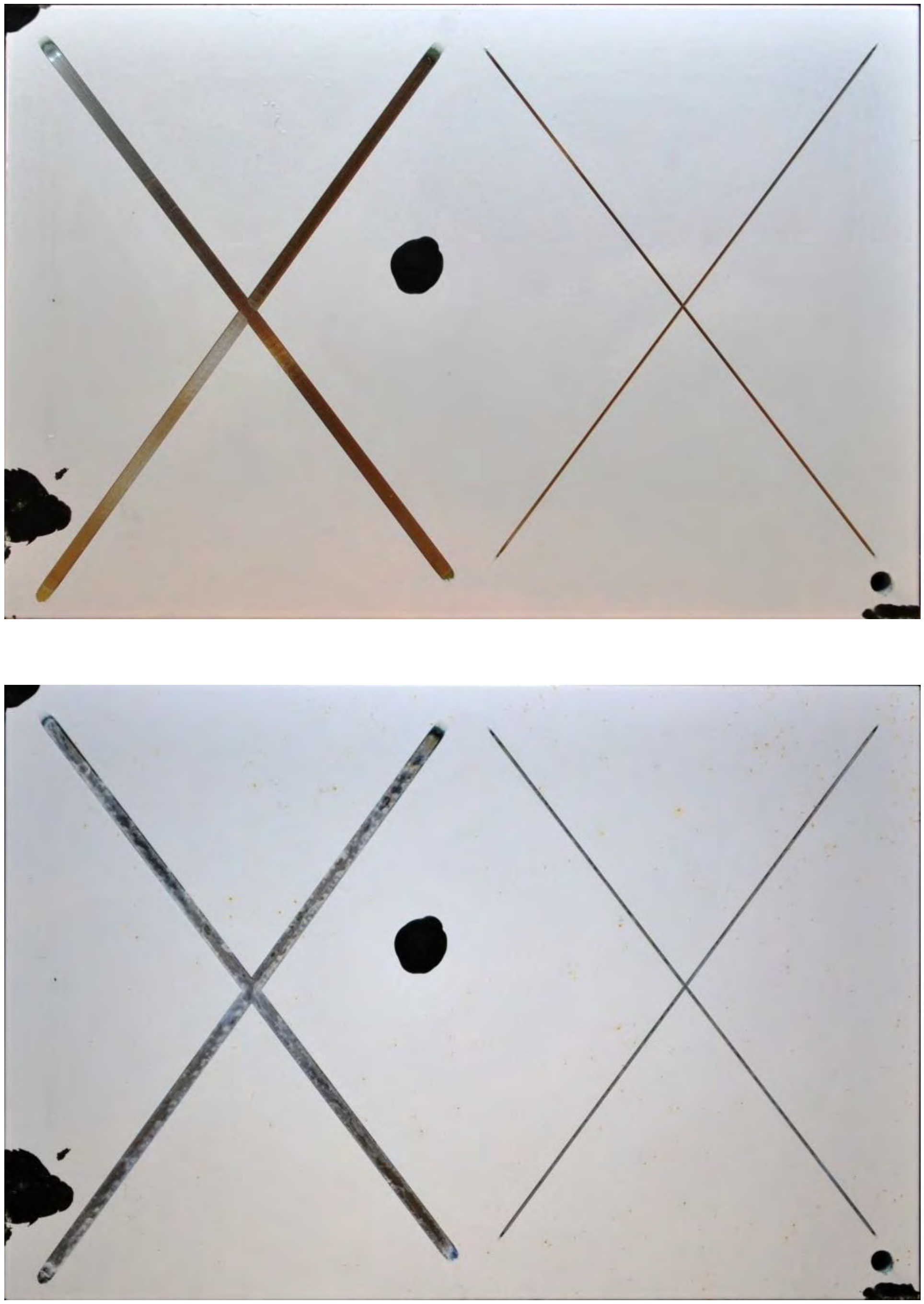

FIGURE 20 – UNS S10500 test panel with zinc-nickel, phosphate, pre-primer, primer, and paint protection scheme prior to test (top) and after 100 hour test (bottom) per ASTM B117. Some blistering of the paint is observed near the scribe lines.

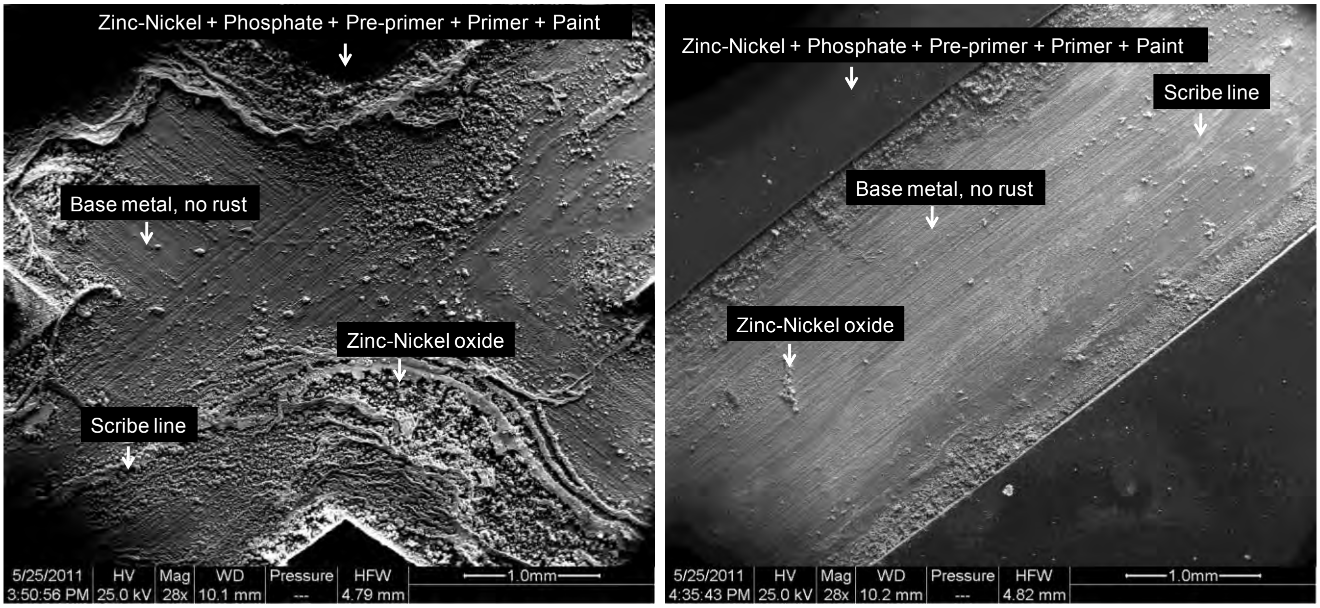

FIGURE 21 – SEM micrograph of UNS S10500 2.5 mm scribe after 100 hour test per ASTM B117. Blistering of the protection scheme can be seen along scribe lines, although not shown in SEM image.

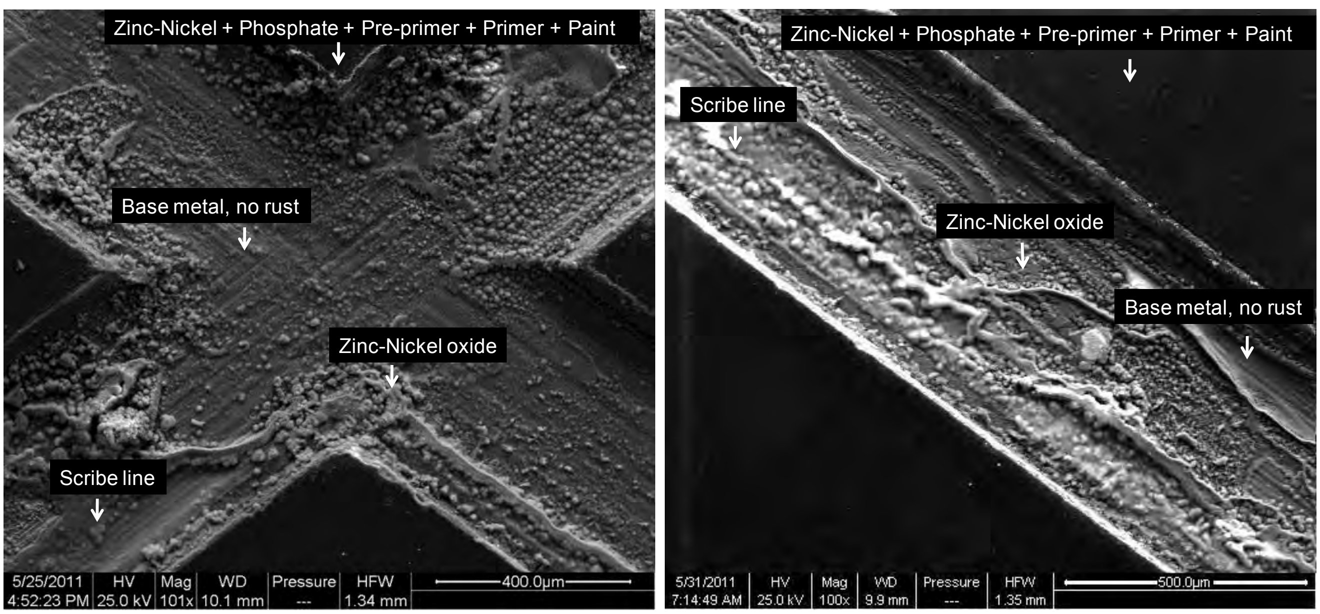

FIGURE 22 - SEM micrograph of UNS S10500 0.5 mm scribe after 100 hour test per ASTM B117. Minor blistering of the protection scheme can be seen along scribe lines, although not shown in SEM image.

UNS S10500 (cadmium + chromate + primer + paint). The UNS S10500 panel with the cadmium, chromate, primer, and paint had no undercutting or blistering present, as seen in Figure 23. Figure 24 shows that the 2.5 mm scribe intersection and scribe contained regions of base metal and cadmium oxide. Similarly, Figure 25 indicates base metal and cadmium oxide in the intersection and along the scribe line of the 0.5 mm scribe.

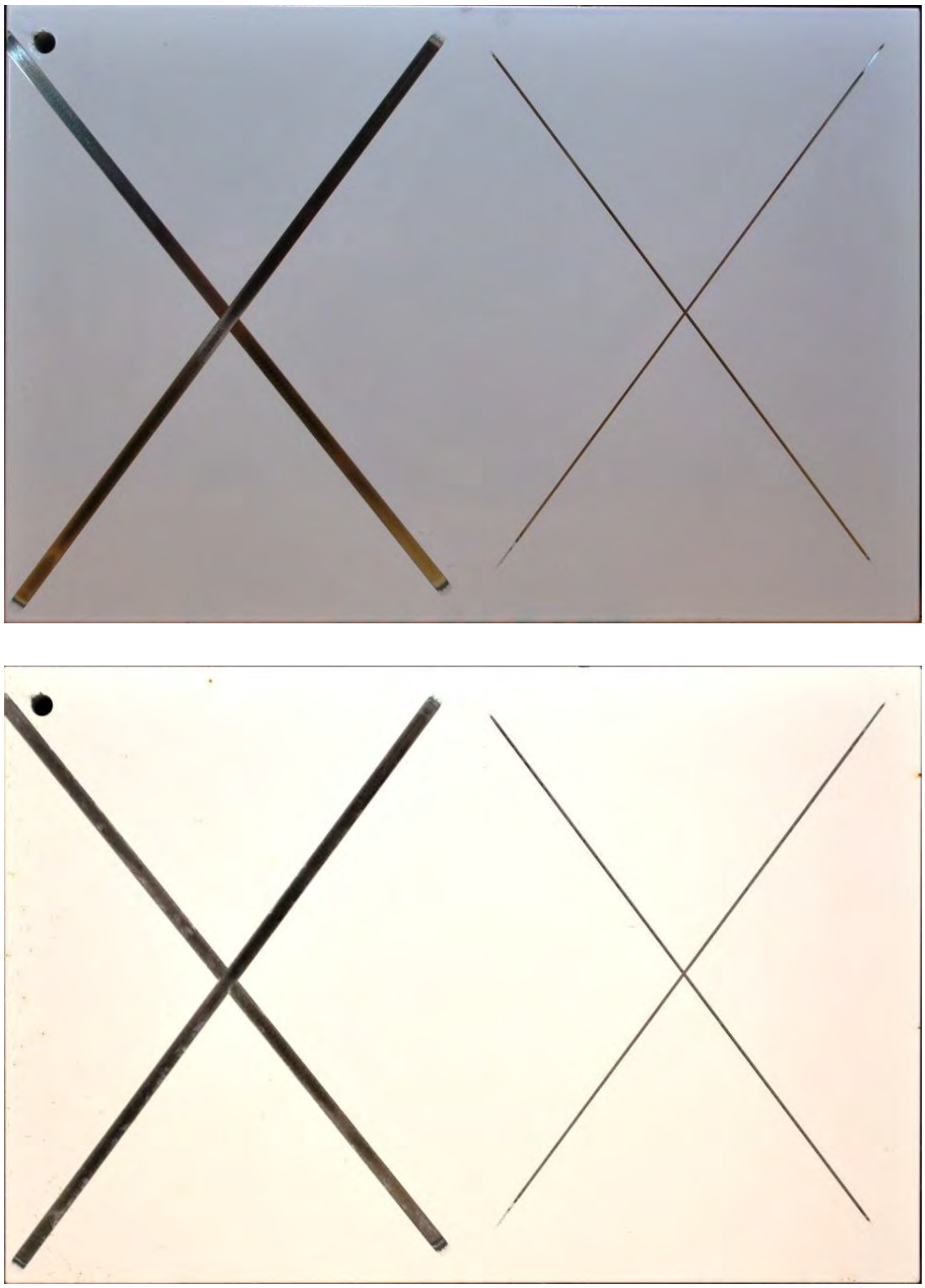

FIGURE 23 – UNS S10500 test panel with cadmium, chromate, primer, and paint protection scheme prior to test (top) and after 100 hour test (bottom) per ASTM B117. No blistering or undercutting of the protection scheme was observed.

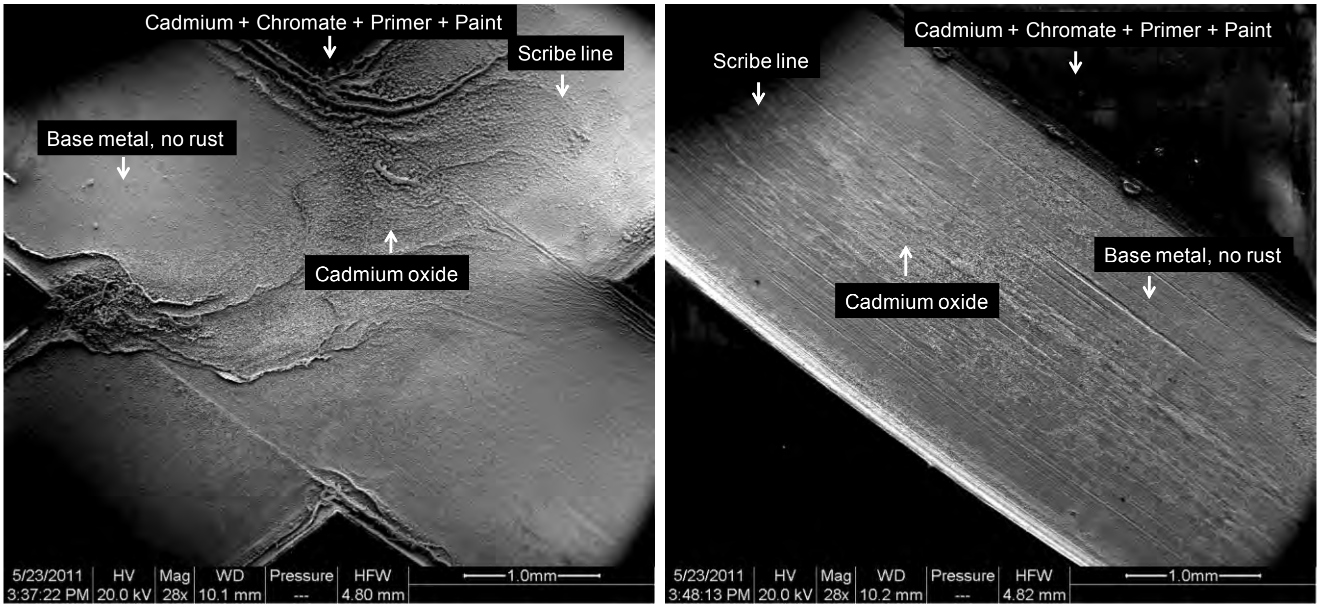

FIGURE 24 – SEM micrograph of UNS S10500 2.5 mm scribe after 100 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis.

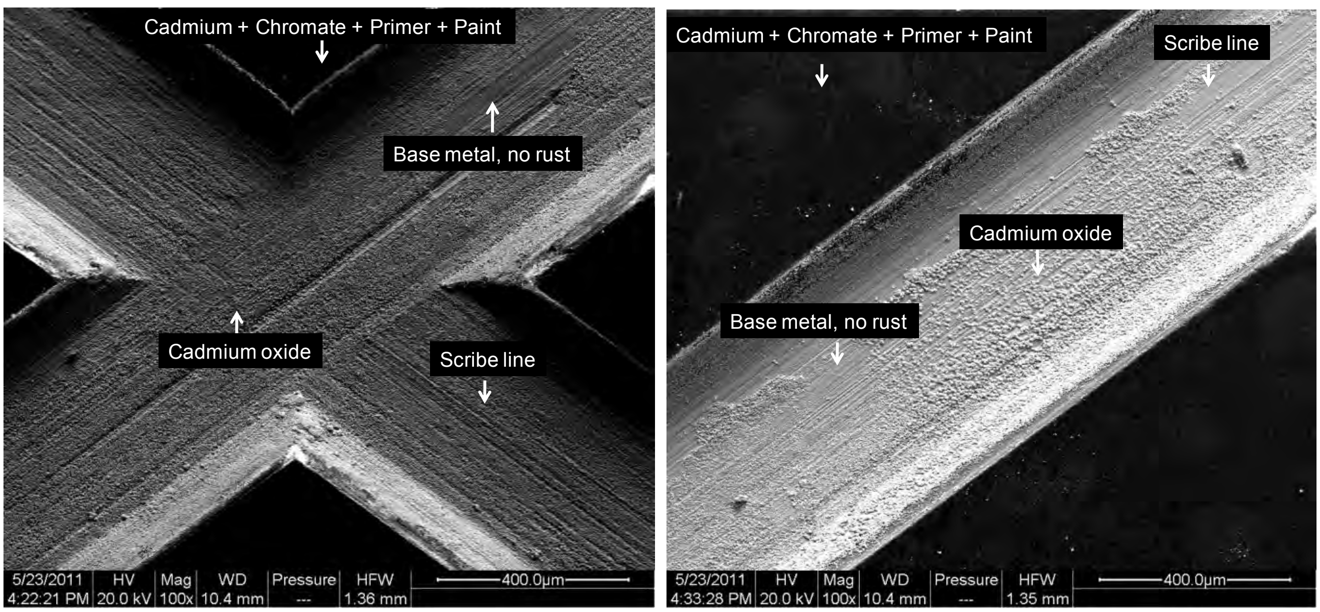

FIGURE 25 – SEM micrograph of UNS S10500 0.5 mm scribe after 100 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis.

500 hour test

UNS G43400 (cadmium + chromate + primer + paint). The UNS G43400 test panel with the cadmium, chromate, primer, and paint protection scheme exhibited dense blistering in the 2.5 mm scribes and a few blisters along the 0.5 mm scribes, as seen in Figure 26. Figure 27 indicates rust, cadmium oxide, and base metal were present in the 2.5 mm scribe intersection and along the line. Likewise, rust, cadmium oxide, and base metal were present in the 0.5 mm scribe intersection and line, as seen in Figure 28.

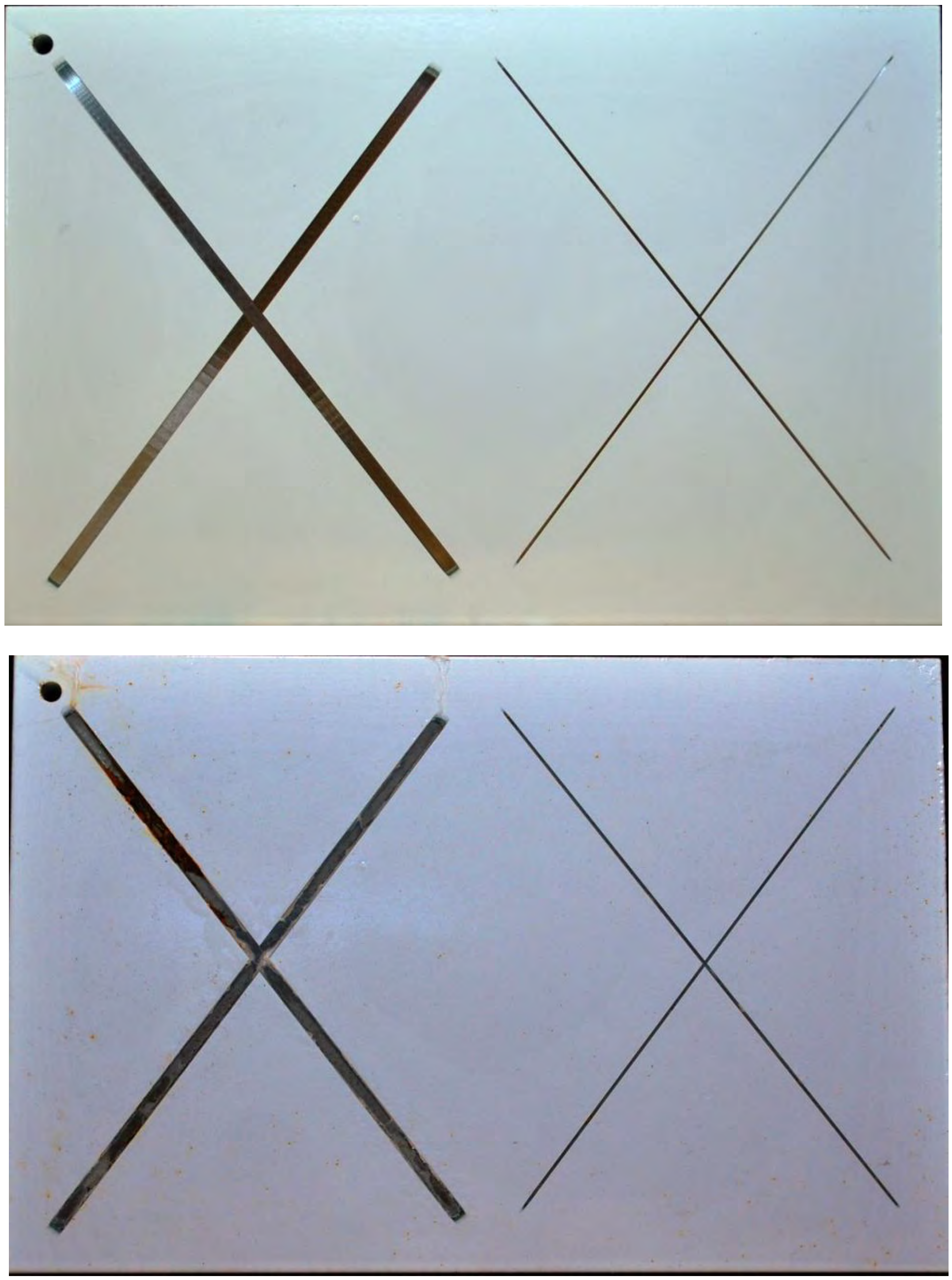

Figure 26 - UNS G43400 test panel with cadmium, chromate, primer, and paint protection scheme prior to test (top) and after 500 hour test (bottom) per ASTM B117. While the appearance of iron oxide corrosion product was present and some blistering near the scribes, there was no undercutting of the protection scheme.

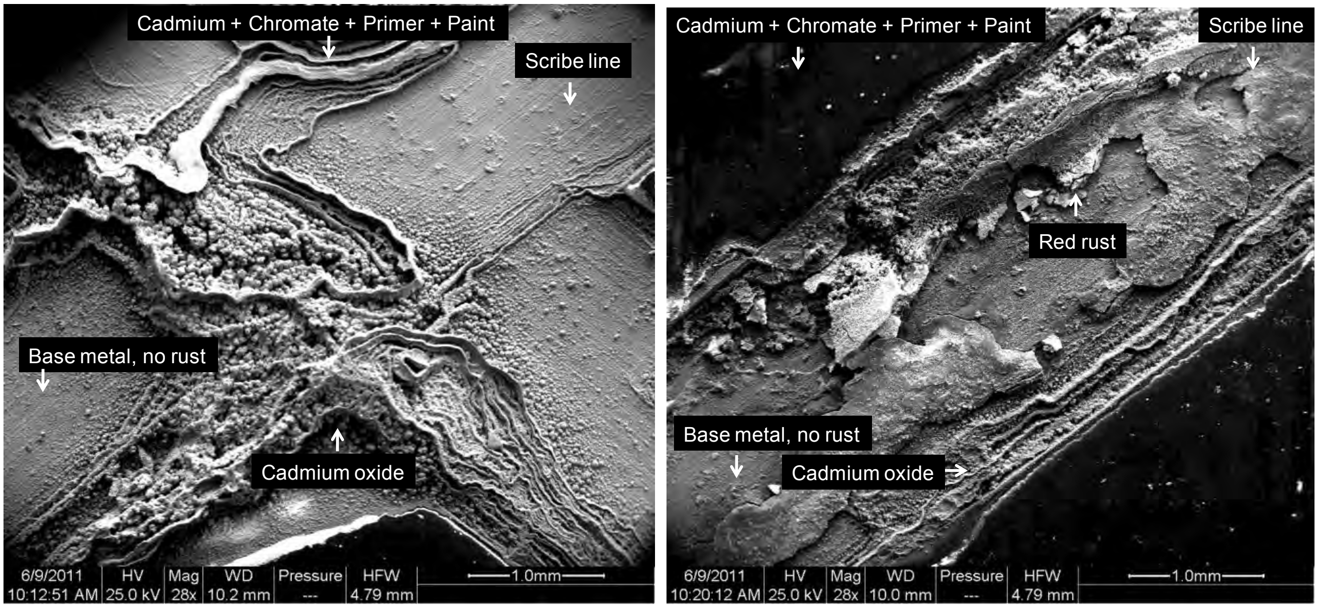

Figure 27 – SEM micrograph of UNS G43400 2.5 mm scribe after 500 hour test per ASTM B117. Blistering of the protection scheme was observed during the analysis (not visible in the figure). Iron oxide corrosion product was contained within the length of the scribe.

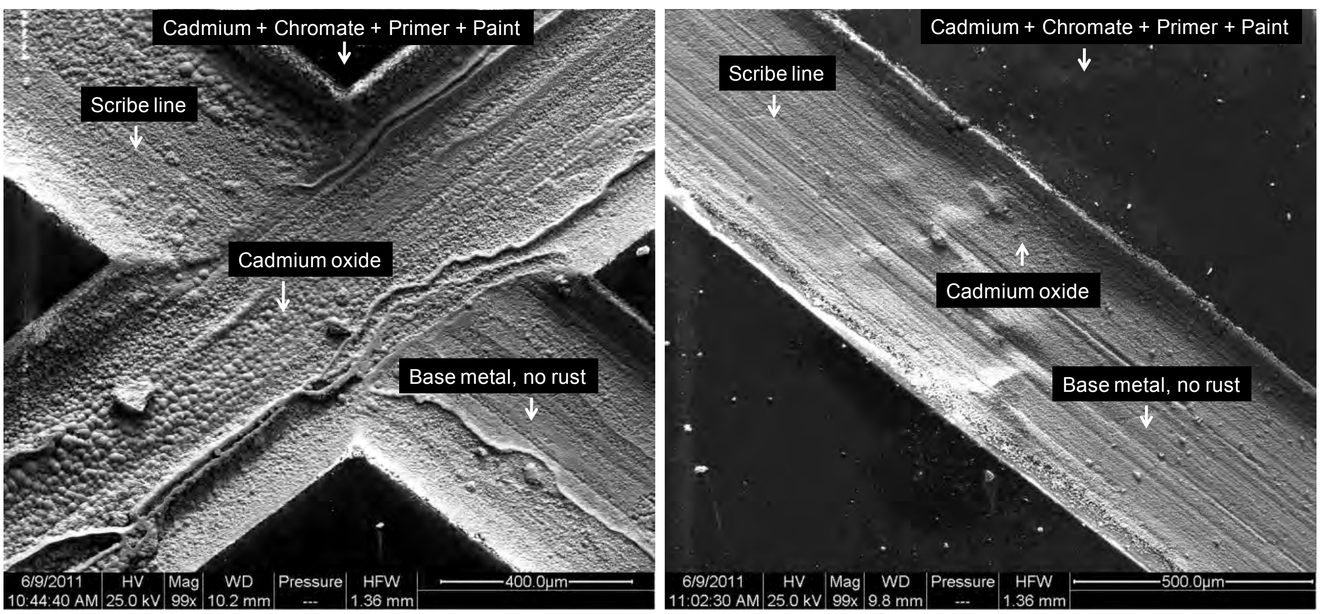

Figure 28 – SEM micrograph of UNS G43400 0.5 mm scribe after 500 hour test per ASTM B117. Minor blistering of the protection scheme was observed during the analysis. Iron oxide corrosion product was visually present within the length of the scribe (not shown).

UNS K44220 (cadmium + chromate + primer + paint). The UNS K44220 test panel with the cadmium, chromate, primer, and paint protection scheme displayed dense blistering along the 2.5 mm scribes and a few blisters along the 0.5 mm scribes, shown in Figure 29. Undercutting is present near the intersection of the 2.5 mm scribe lines. Figure 30 shows regions in the 2.5 mm scribe intersection and along the scribe line that are either cadmium oxide or base metal. Although not shown, localized iron oxide corrosion product is also present along the scribe lines. Figure 31 shows the presence of cadmium oxide and base metal in the 0.5 mm intersection and along the scribe line, though localized iron oxide corrosion product is also present further along the scribe line.

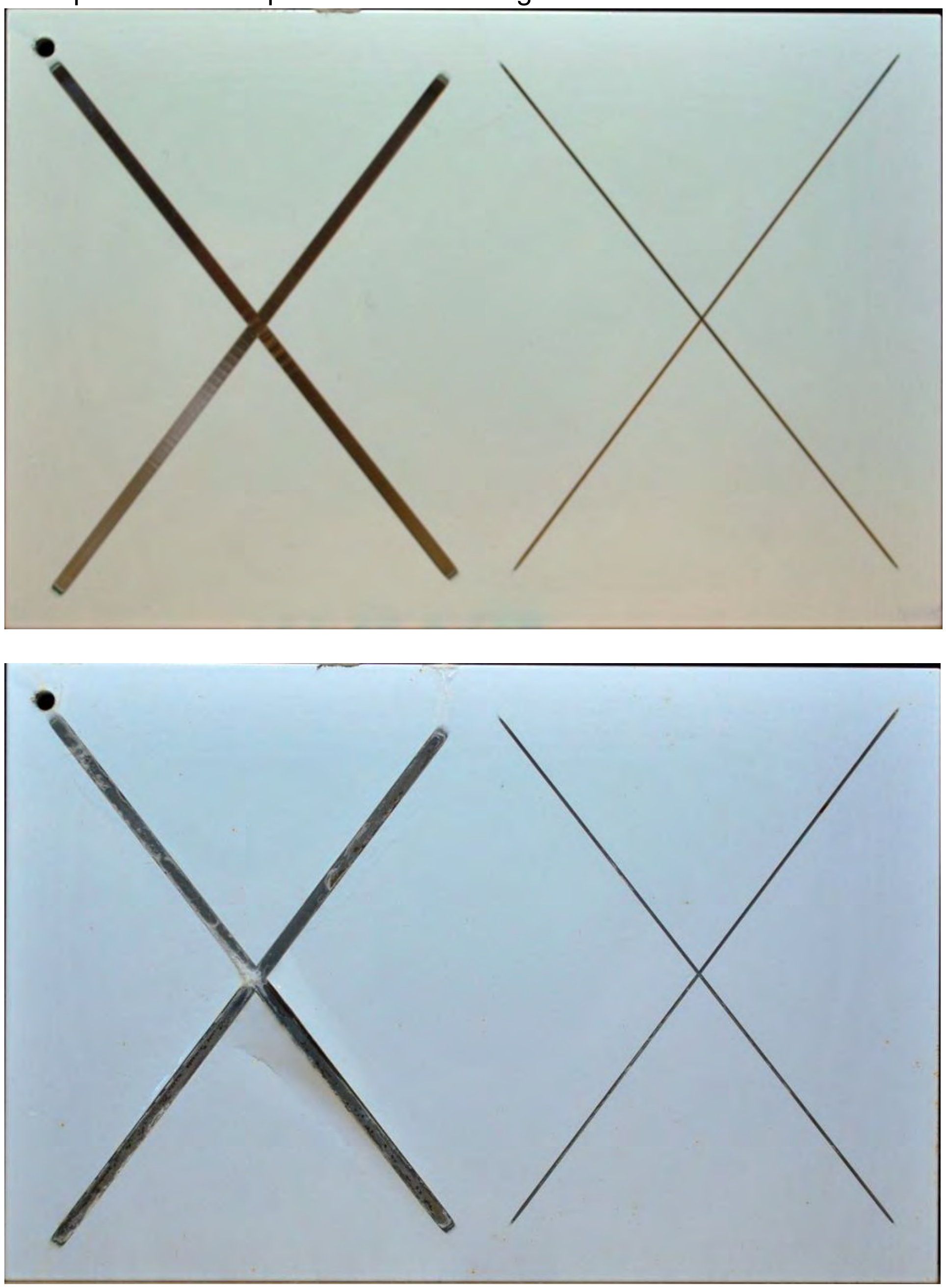

Figure 29 - UNS K44220 test panel with cadmium, chromate, primer, and paint protection scheme prior to test (top) and after 500 hour test (bottom) per ASTM B117. Iron oxide corrosion product was present, as well as some blistering near the scribes. Undercutting of the protection scheme was visible along the 2.5 mm scribe.

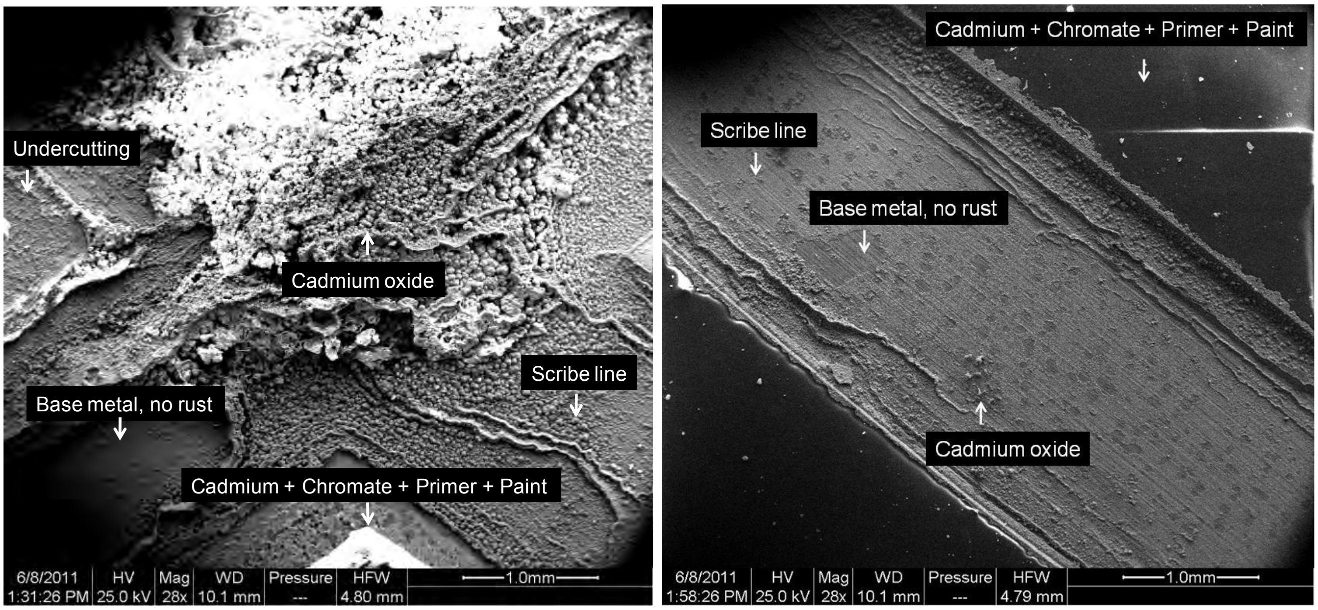

Figure 30 – SEM micrograph of UNS K44220 2.5 mm scribe after 500 hour test per ASTM B117. Blistering and undercutting of the protection scheme was observed near the intersection of the scribes during the analysis. There was localized iron oxide corrosion product visually present within the length of the scribe, although not visible in the image.

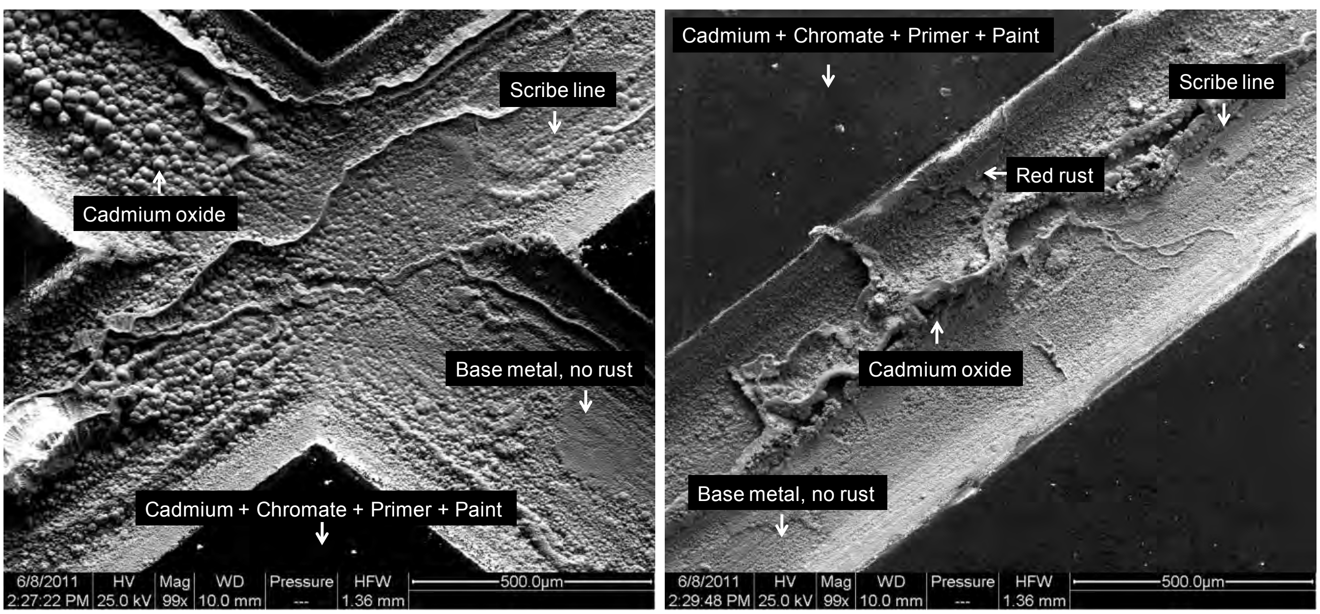

Figure 31 – SEM micrograph of UNS K44220 0.5 mm scribe after 500 hour test per ASTM B117. Some minor blistering of the protection scheme was observed during the analysis (not visible). There was localized iron oxide corrosion product visually present within the length of the scribe.

UNS K92580 (cadmium + chromate + primer + paint). The UNS K92580 panel with the cadmium, chromate, primer, and paint protection scheme (Figure 32) showed blistering only along the 2.5 mm scribe. No undercutting was present. Figures 33 and 34 indicate that cadmium oxide and base metal are present in the intersection and along the scribe line for the 2.5 mm and 0.5 mm scribe widths, respectively.

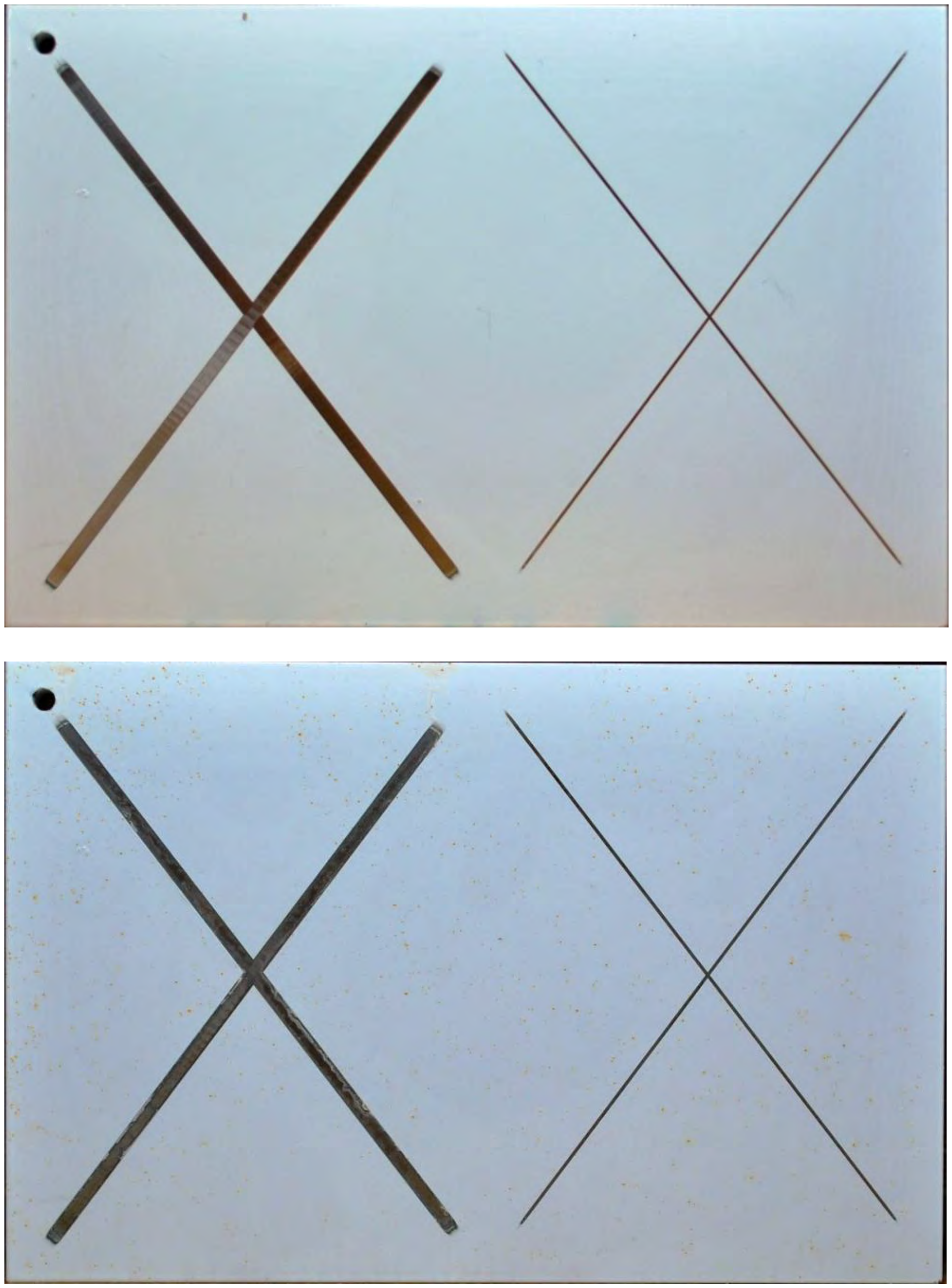

Figure 32 - UNS K92580 test panel with cadmium, chromate, primer, and paint protection scheme prior to test (top) and after 500 hour test (bottom) per ASTM B117. Blistering was present along the 2.5 mm scribe. No undercutting of the protection scheme was observed.

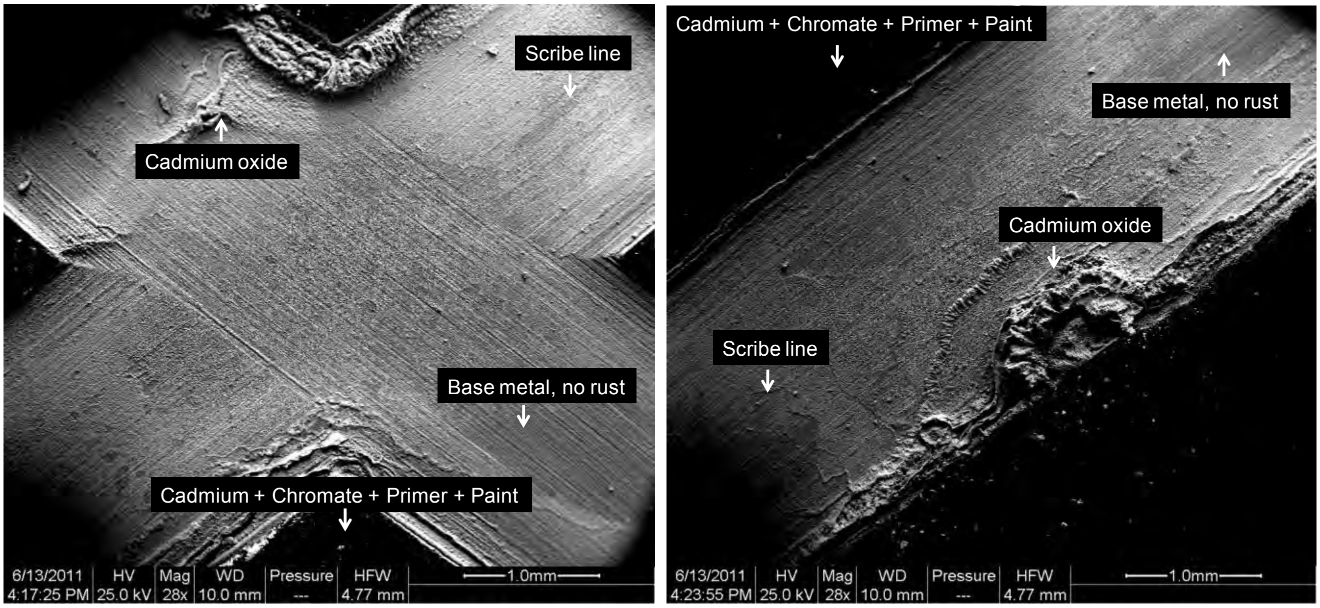

Figure 33 – SEM micrograph of UNS K92580 2.5 mm scribe after 500 hour test per ASTM B117. While blistering was present along the scribe lines, no undercutting of the protection scheme was observed during the analysis.

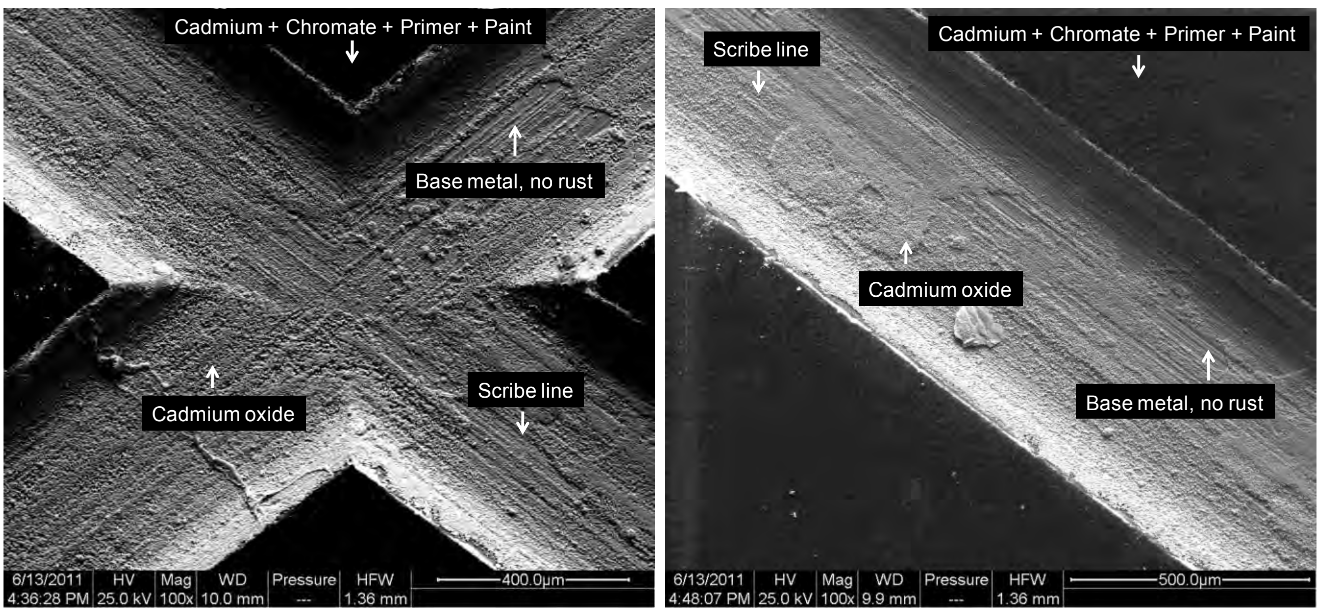

Figure 34 – SEM micrograph of UNS K92580 2.5 mm scribe after 500 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis.

UNS K91973 (zinc-nickel + phosphate + pre-primer + primer + paint). The UNS K91973 panel with the zinc-nickel, phosphate, pre-primer, primer, and paint protection scheme exhibited medium-dense to dense blistering along both the 2.5 mm and the 0.5 mm scribes, as seen in Figure 35. Figure 36 shows regions of zinc-nickel oxide and base metal in the 2.5 mm scribe intersection and along the scribe line. Zinc-nickel oxide and base metal were also the only constituents present in the 0.5 mm scribe intersection and along the scribe line, as seen in Figure 37.

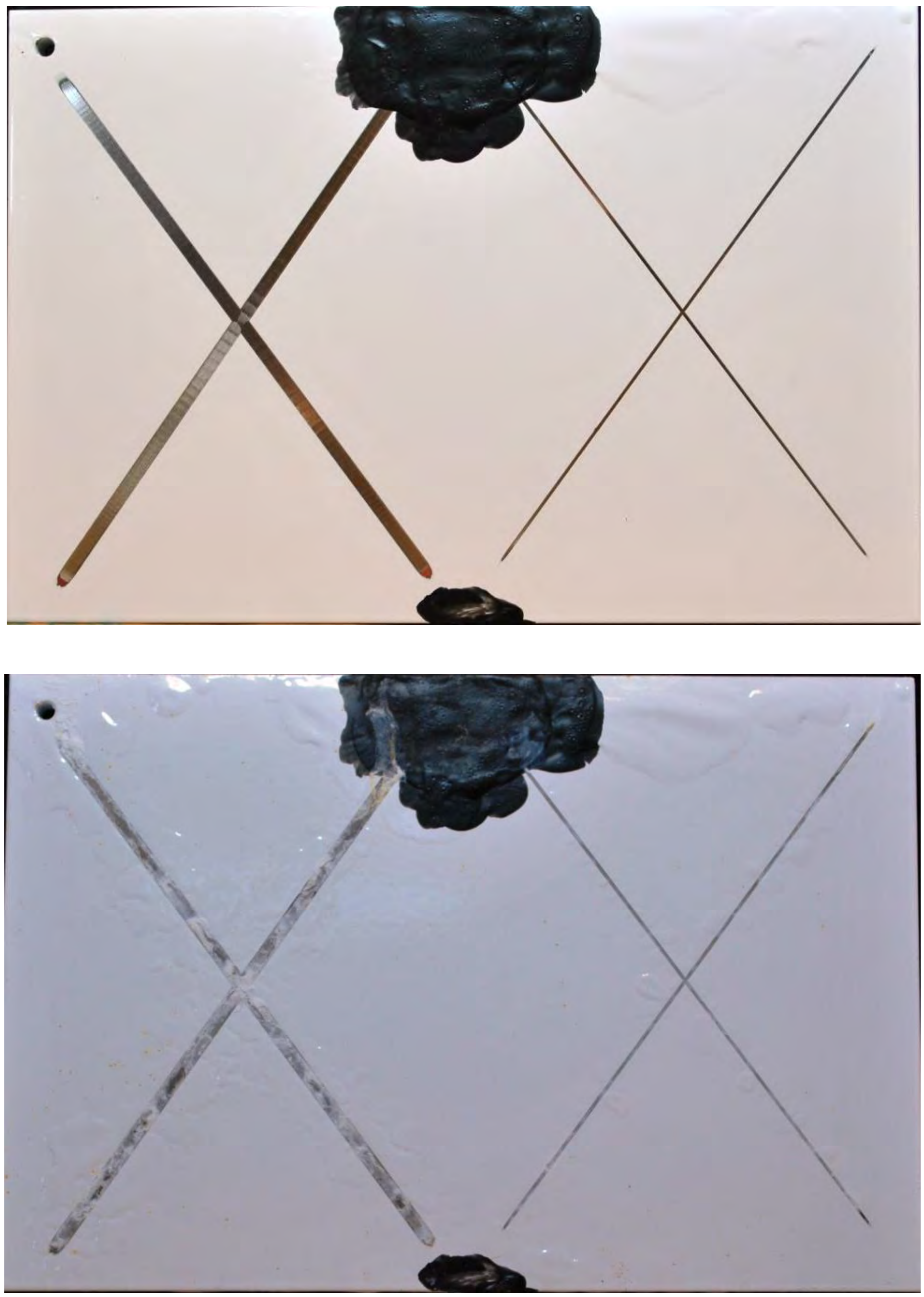

Figure 35 - UNS K91973 test panel with zinc-nickel, phosphate, pre-primer, primer, and paint protection scheme prior to test (top) and after 500 hour test (bottom) per ASTM B117. Blistering of the paint was observed near the scribes.

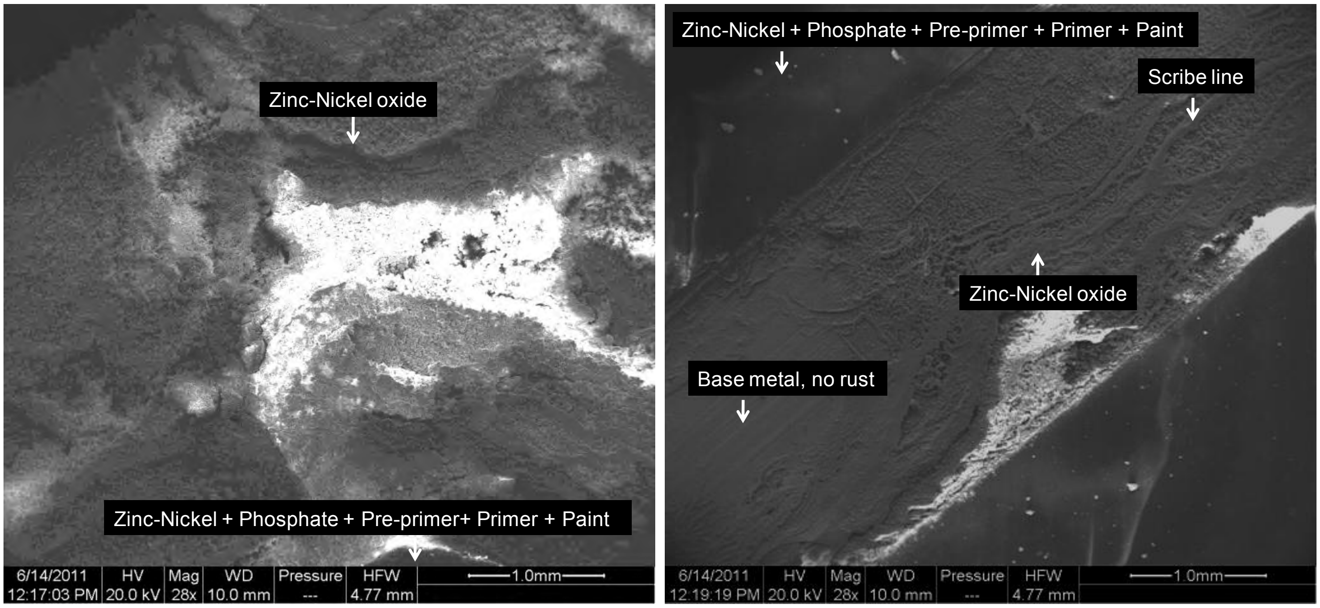

Figure 36 - SEM micrograph of UNS K91973 2.5 mm scribe after 500 hour test per ASTM B117. Blistering of the protection scheme can be seen along scribe lines, although not visible in SEM image.

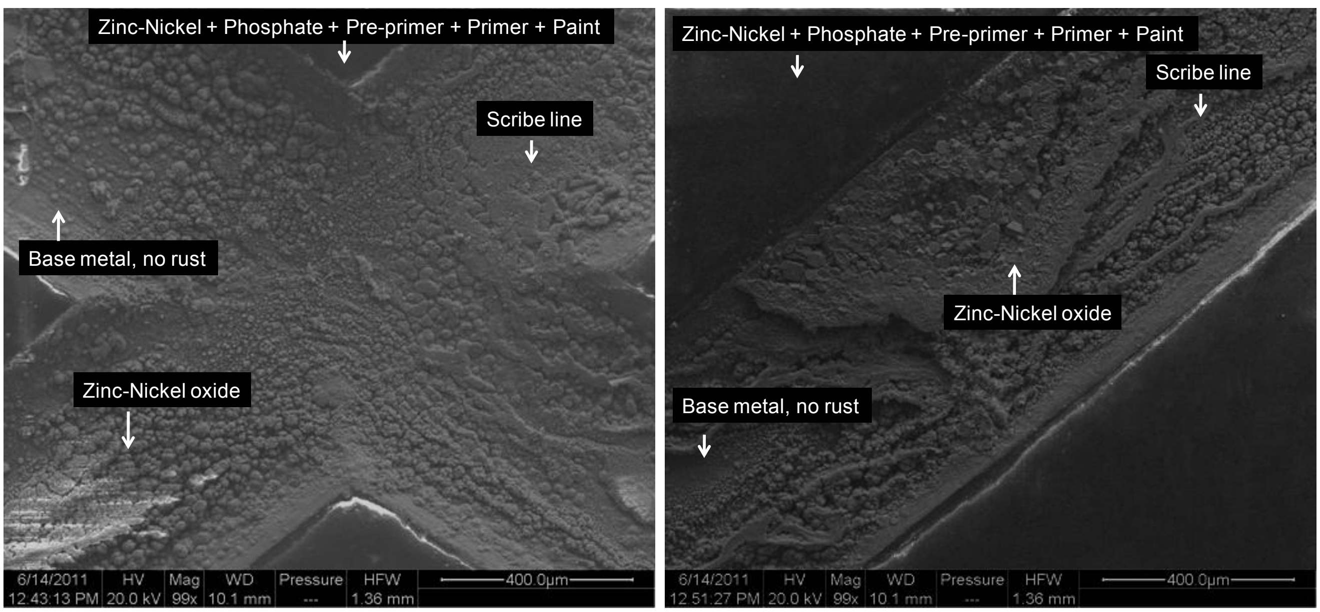

Figure 37 - SEM micrograph of UNS K91973 0.5 mm scribe after 500 hour test per ASTM B117. Blistering of the protection scheme can be seen along scribe lines, although not shown in SEM image.

UNS K91973 (cadmium + chromate + primer + paint). The UNS K91973 panel with the cadmium, chromate, primer, and paint protection scheme produced very few minor blisters and no undercutting along the scribes (Figure 38). Figure 39 shows cadmium oxide and base metal are present on the 2.5 mm scribe intersection and further down one of the scribes. Likewise, cadmium oxide and base metal are present along the 0.5 mm scribe intersection and scribe line (Figure 40).

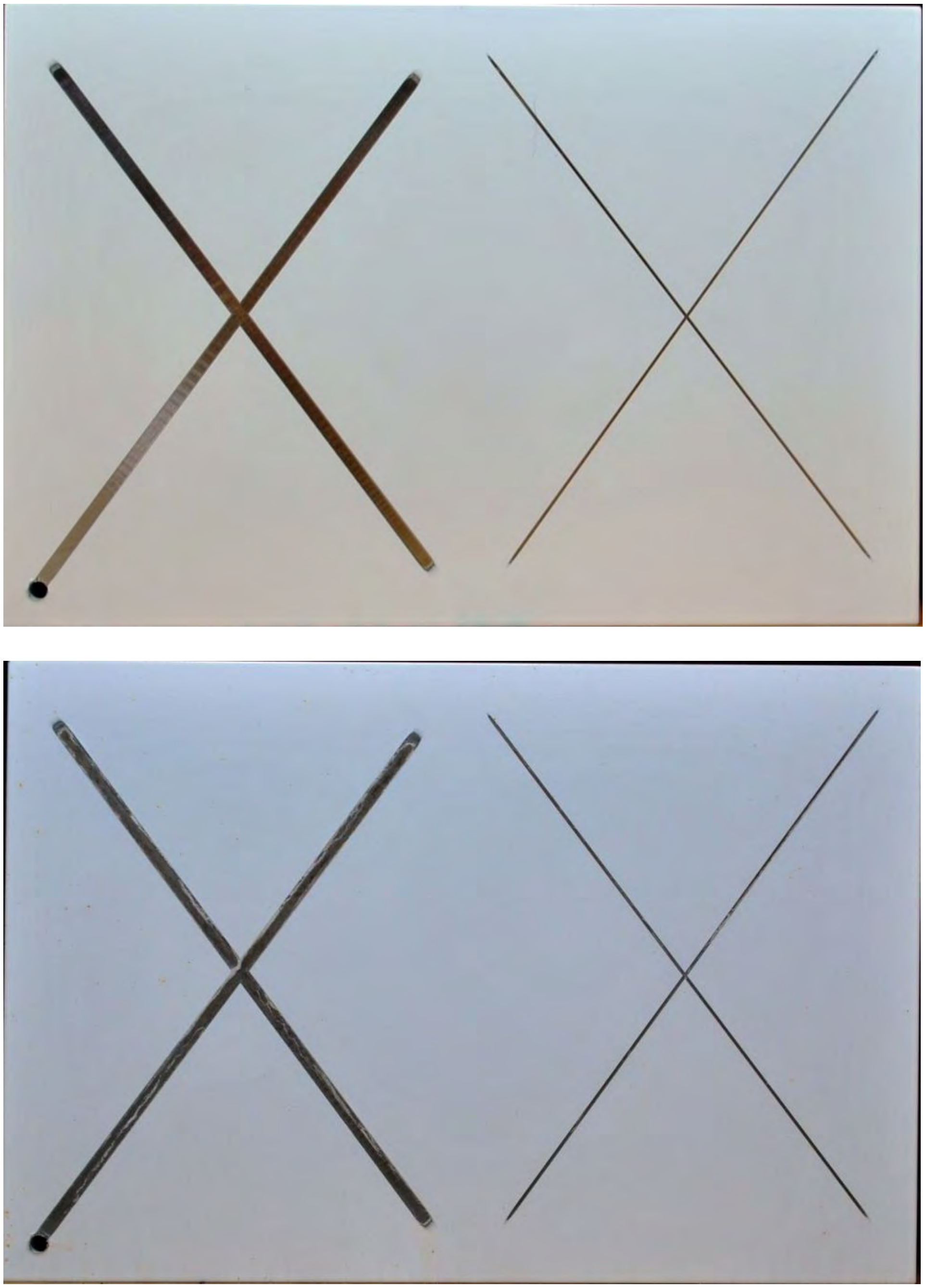

Figure 38 – UNS K91973 test panel with cadmium, chromate, primer, and paint protection scheme prior to test (top) and after 500 hour test (bottom) per ASTM B117. Minor blistering and no undercutting of the protection scheme were observed.

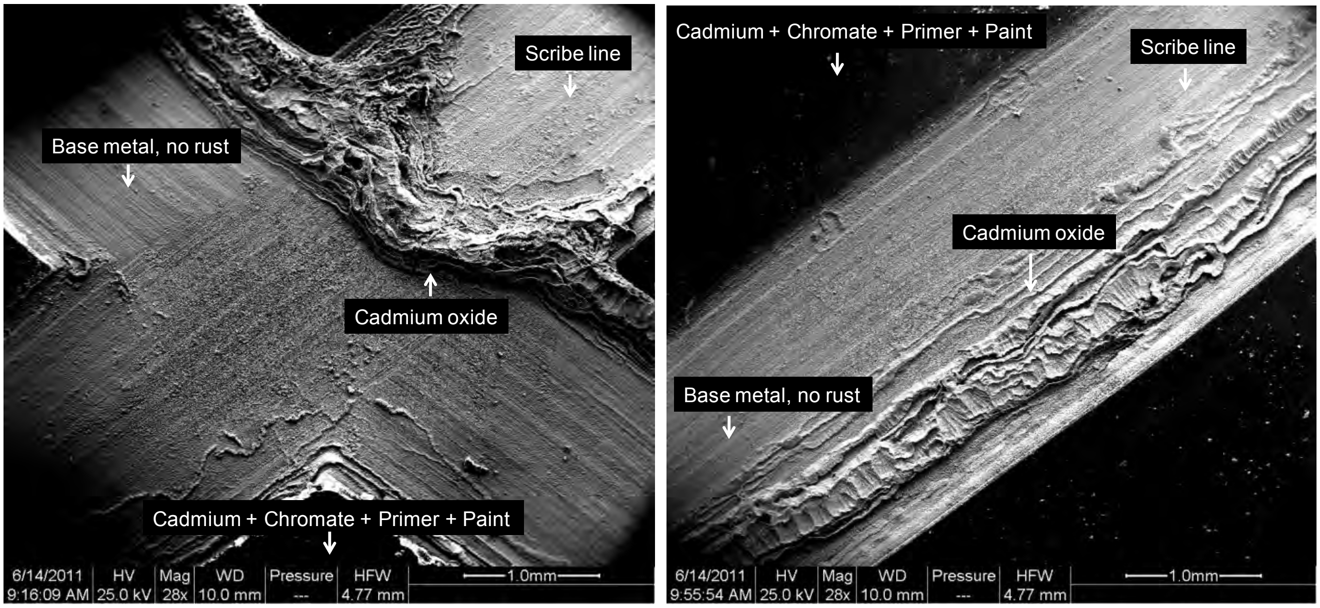

Figure 39 – SEM micrograph of UNS K91973 2.5 mm scribe after 500 hour test per ASTM B117. No undercutting of the protection scheme was observed during the analysis, though a few blisters along the scribe line are present (not shown).

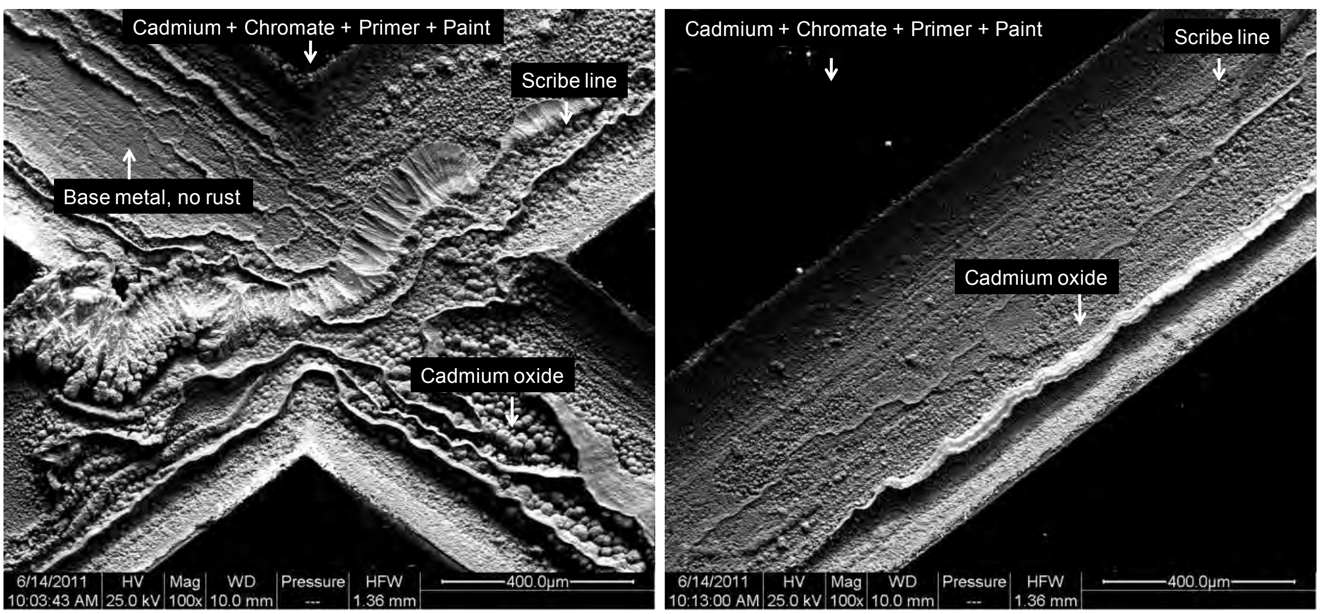

Figure 40 – SEM micrograph of UNS K91973 0.5 mm scribe after 500 hour test per ASTM B117. A few small blisters were observed along the scribe line. No undercutting of the protection scheme was observed during the analysis.

<u>UNS S10500 (pre-primer + primer + paint)</u>. The UNS S10500 panel with the pre-primer, primer, and paint panel displayed a few minor blisters along both the 2.5 mm and 0.5 mm scribes, although undercutting is only present along the 2.5 mm scribe, as shown in Figure 41. Localized corrosion product and base metal are present in the intersection and along the scribe line for the 2.5 mm and 0.5 mm scribe widths (Figures 42 and 43, respectively).

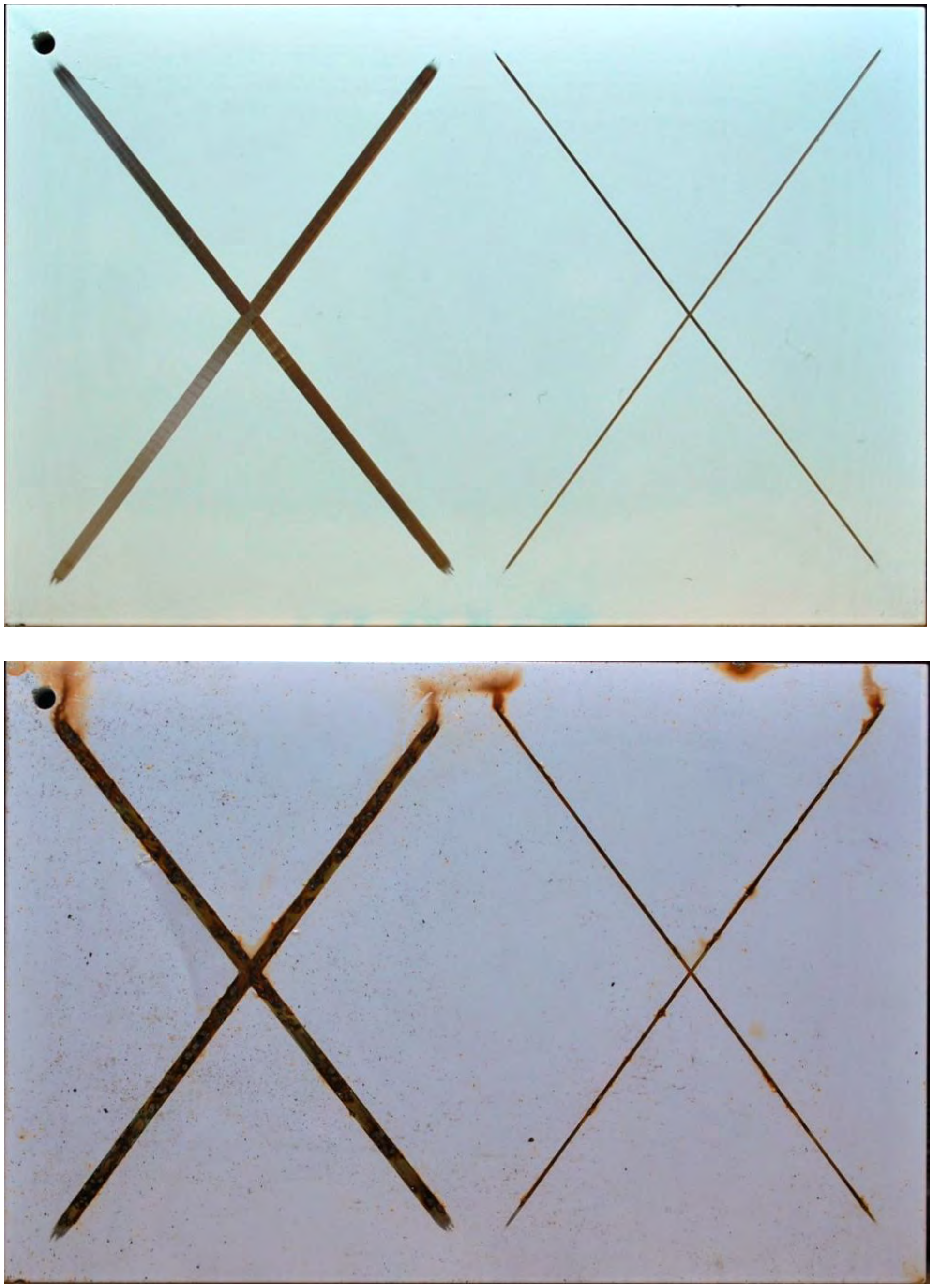

Figure 41 – UNS S10500 test panel with pre-primer, primer, and paint protection scheme prior to test (top) and after 500 hour test (bottom) per ASTM B117. Localized iron oxide corrosion product was present, as well as small blisters along the scribes. There was evidence of undercutting of the protection scheme visible on the 2.5 mm scribe.

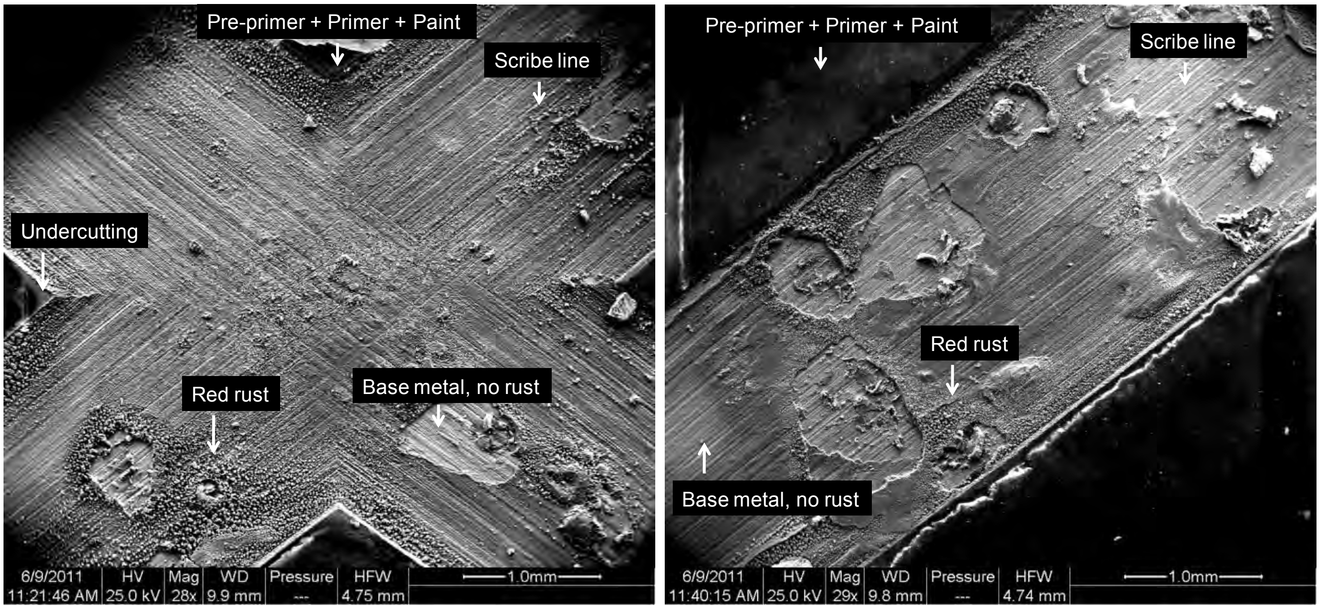

Figure 42 – SEM micrograph of UNS S10500 2.5 mm scribe after 500 hour test per ASTM B117. Minor undercutting of the protection scheme was observed at the intersection of the scribes during the analysis. Also, a few minor blisters were present along the scribe (not visible in the SEM image). There was localized iron oxide corrosion product contained within the length of the scribe.

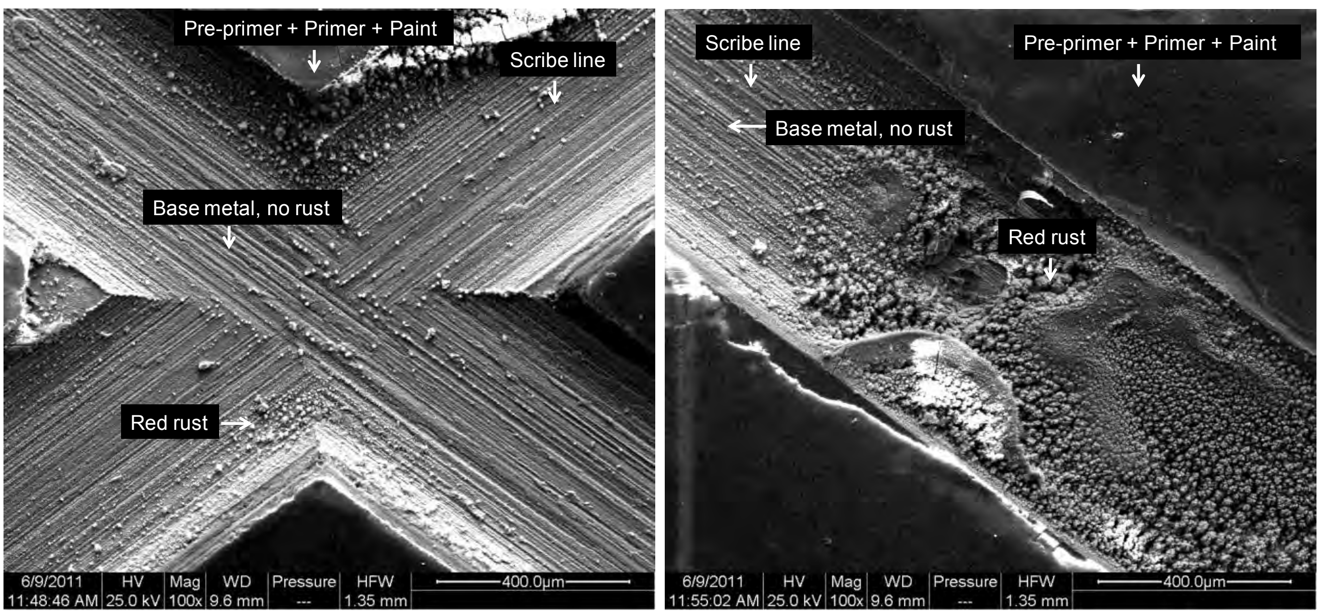

Figure 43 – SEM micrograph of UNS S10500 0.5 mm scribe after 500 hour test per ASTM B117. No undercutting of the protection scheme was observed during the analysis. Some small blisters were present along the scribe (not visible in the SEM image). There was localized iron oxide corrosion product contained within the length of the scribe.

UNS S10500 (zinc-nickel + phosphate + pre-primer + primer + paint). The UNS S10500 panel with the zinc-nickel, phosphate, pre-primer, primer, and paint protection scheme exhibited blistering and no undercutting along the scribe lines, as shown in Figure 44. Figures 45 and 46 indicate zinc-nickel oxide as well as bare metal regions in the intersections and along the scribe lines of the 2.5 mm and 0.5 mm scribes, respectively.

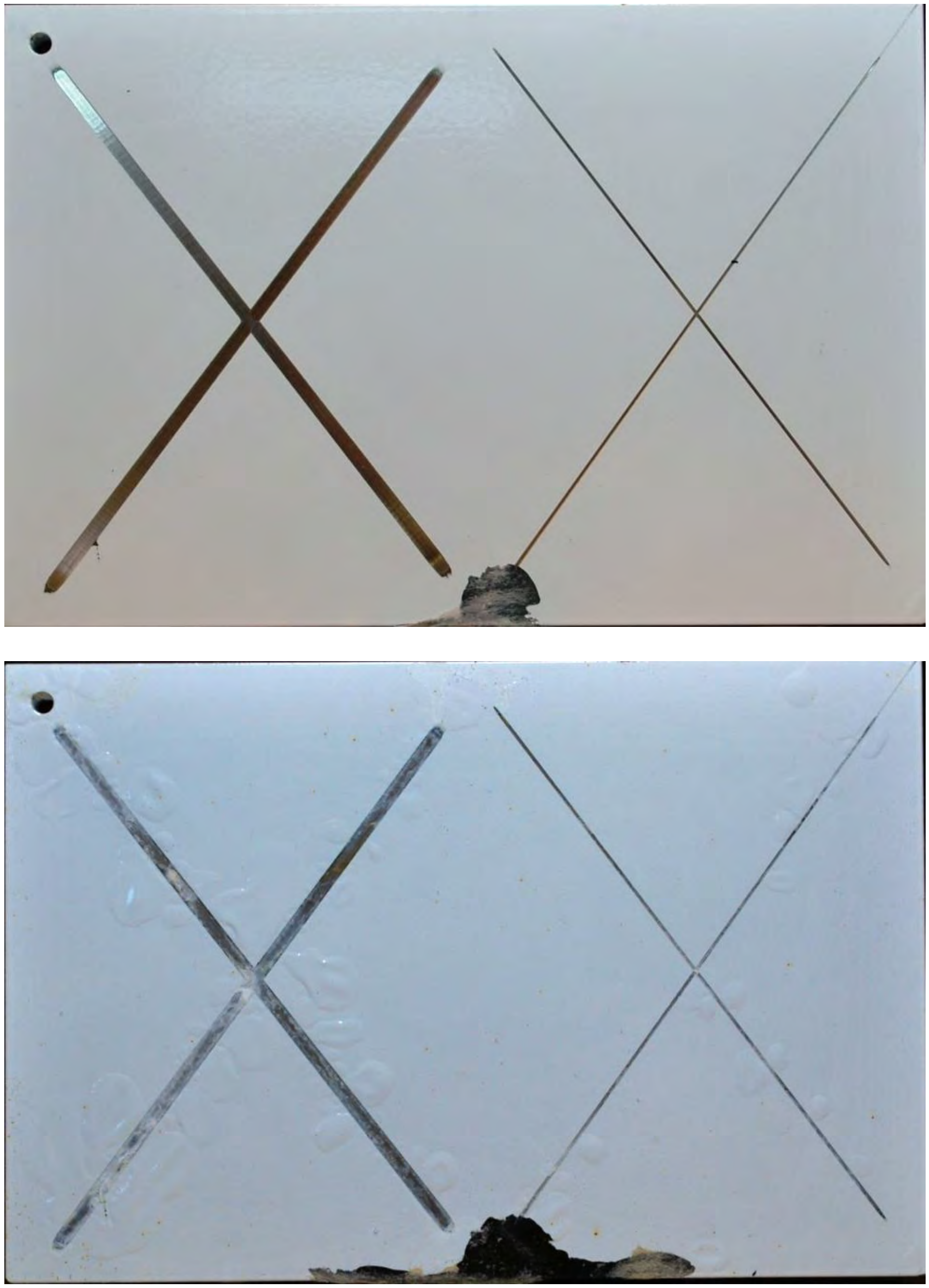

Figure 44 – UNS S10500 test panel with zinc-nickel, phosphate, pre-primer, primer, and paint protection scheme prior to test (top) and after 500 hour test (bottom) per ASTM B117. Blistering of the paint is observed near the scribe lines.

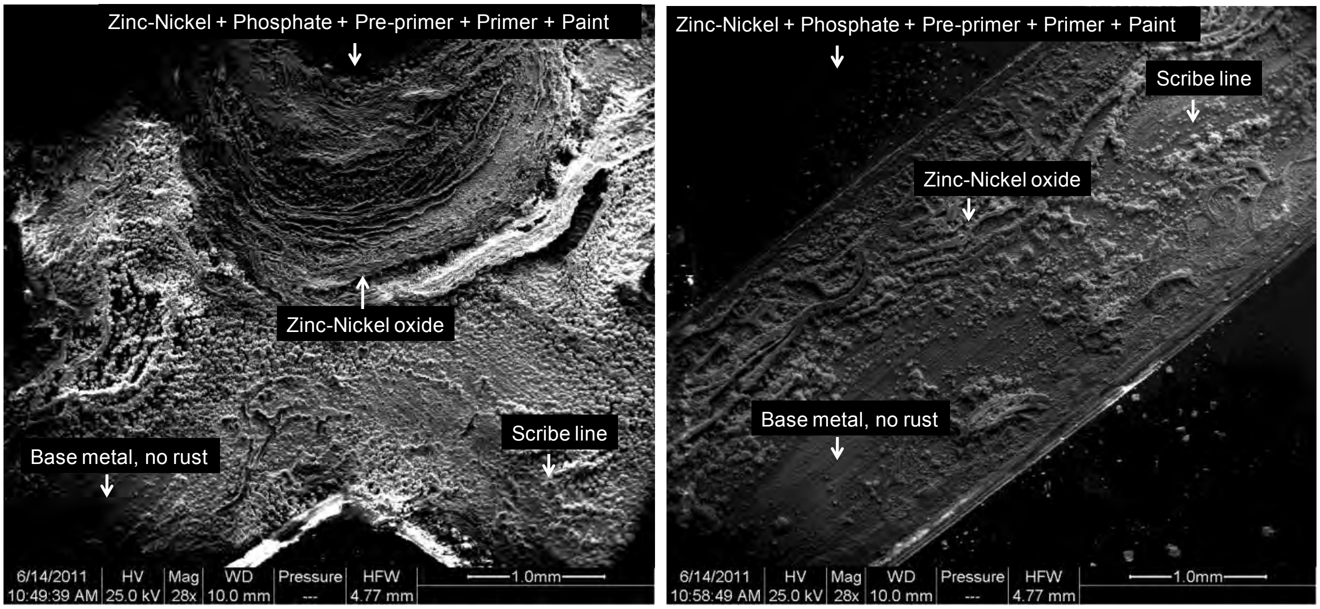

Figure 45 – SEM micrograph of UNS S10500 2.5 mm scribe after 500 hour test per ASTM B117. Blistering of the protection scheme can be seen along scribe lines, although not shown in SEM image.

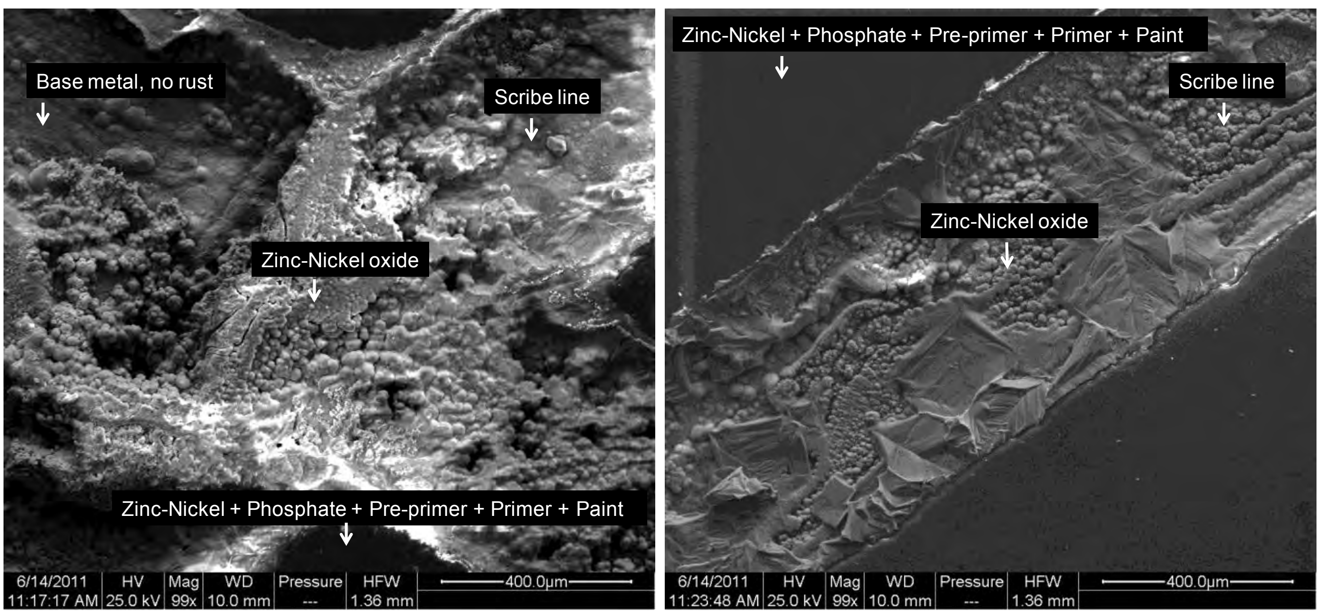

Figure 46 – SEM micrograph of UNS S10500 2.5 mm scribe after 500 hour test per ASTM B117. Minor blistering of the protection scheme can be seen along scribe lines, although not shown in SEM image.

UNS S10500 (cadmium + chromate + primer + paint). The UNS S10500 panel with the cadmium, chromate, primer, and paint had no undercutting present along either of the scribes and only a few minor blisters present along the 2.5 mm wide scribe lines, as seen in Figure 47. Figure 48 shows that the 2.5 mm intersection and scribe lines have regions of cadmium oxide and base metal. Similarly, Figure 49 indicates cadmium oxide and base metal in the intersection and along the scribe lines of the 0.5 mm scribe.

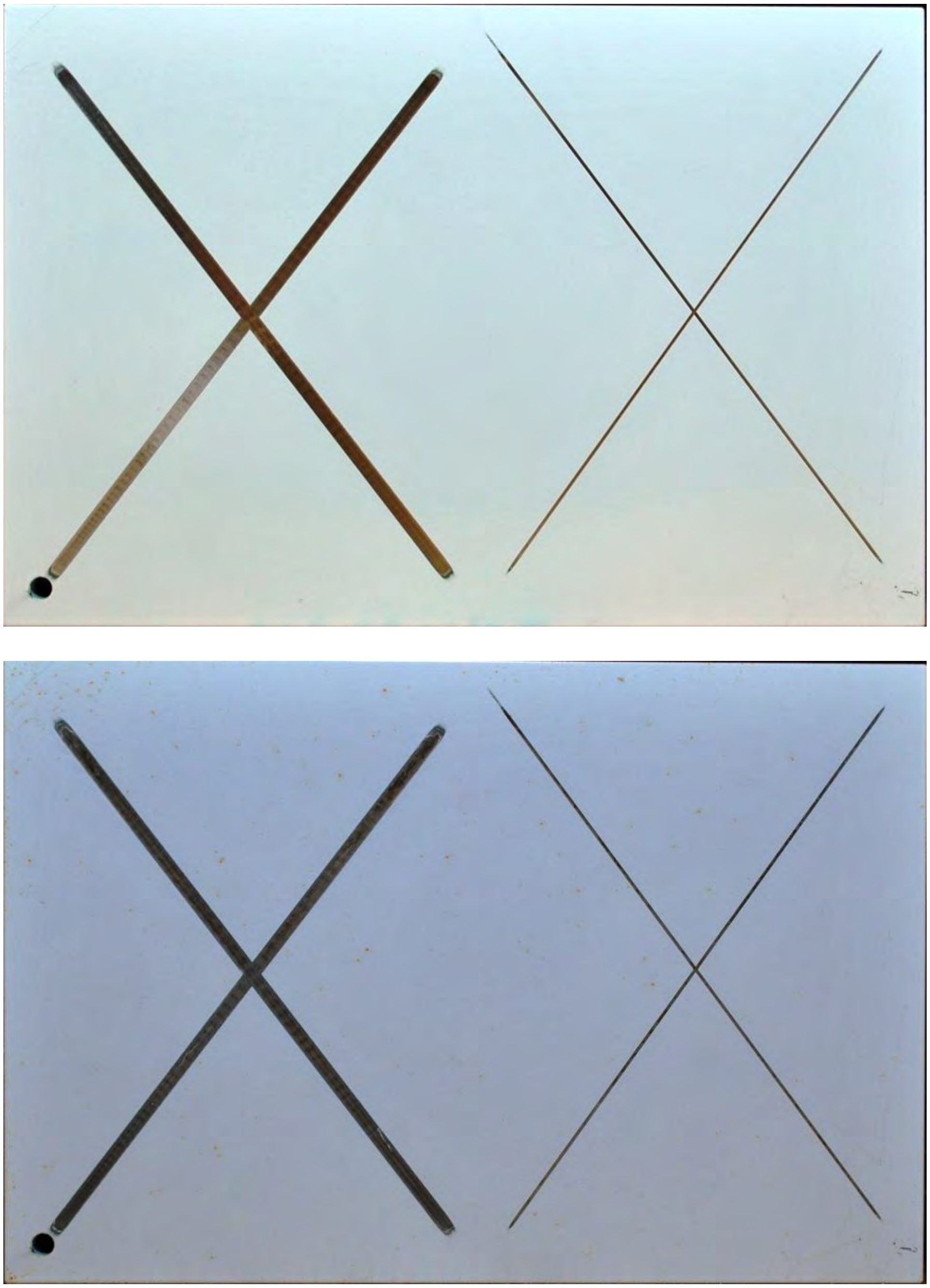

Figure 47 – UNS S10500 test panel with cadmium, chromate, primer, and paint protection scheme prior to test (top) and after 500 hour test (bottom) per ASTM B117. A few minor blisters along the 2.5 mm scribe lines are present. No undercutting of the protection scheme was observed.

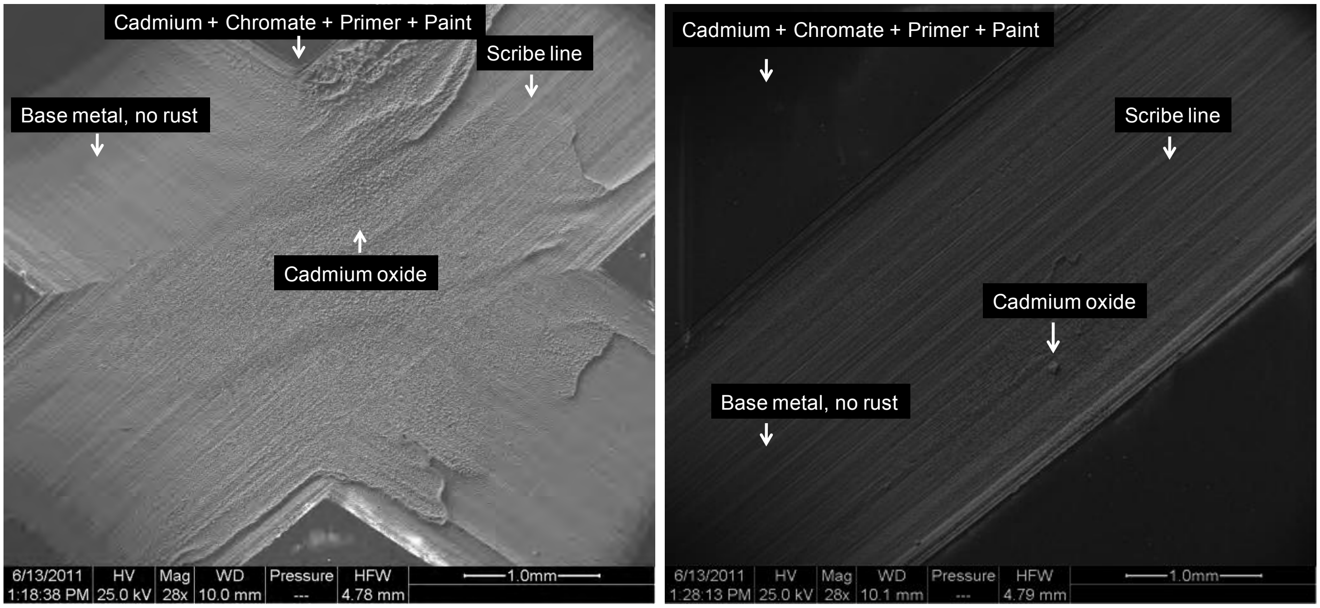

Figure 48 – SEM micrograph of UNS S10500 2.5 mm scribe after 500 hour test per ASTM B117. Although not shown, a few minor blisters are present along the length of the scribe. No undercutting of the protection scheme was observed during the analysis.

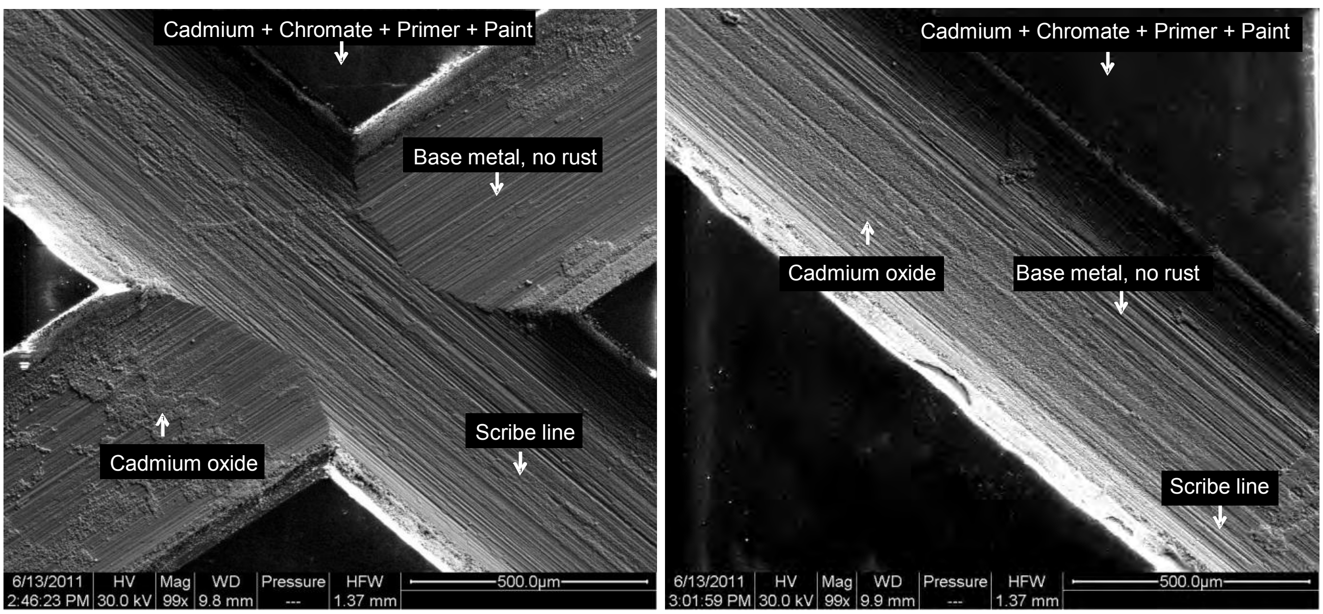

Figure 49 – SEM micrograph of UNS S10500 0.5 mm scribe after 500 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis.

UNS S15500 (pre-primer + primer + paint). The UNS S15500 panel with the pre-primer, primer, and paint had no undercutting or blistering present, as seen in Figure 50. Figure 51 shows that pitting is only present along the 2.5 mm scribe line, and base metal is present everywhere else. Only base metal was present in the intersection and along the 0.5 mm scribe, as seen in Figure 52.

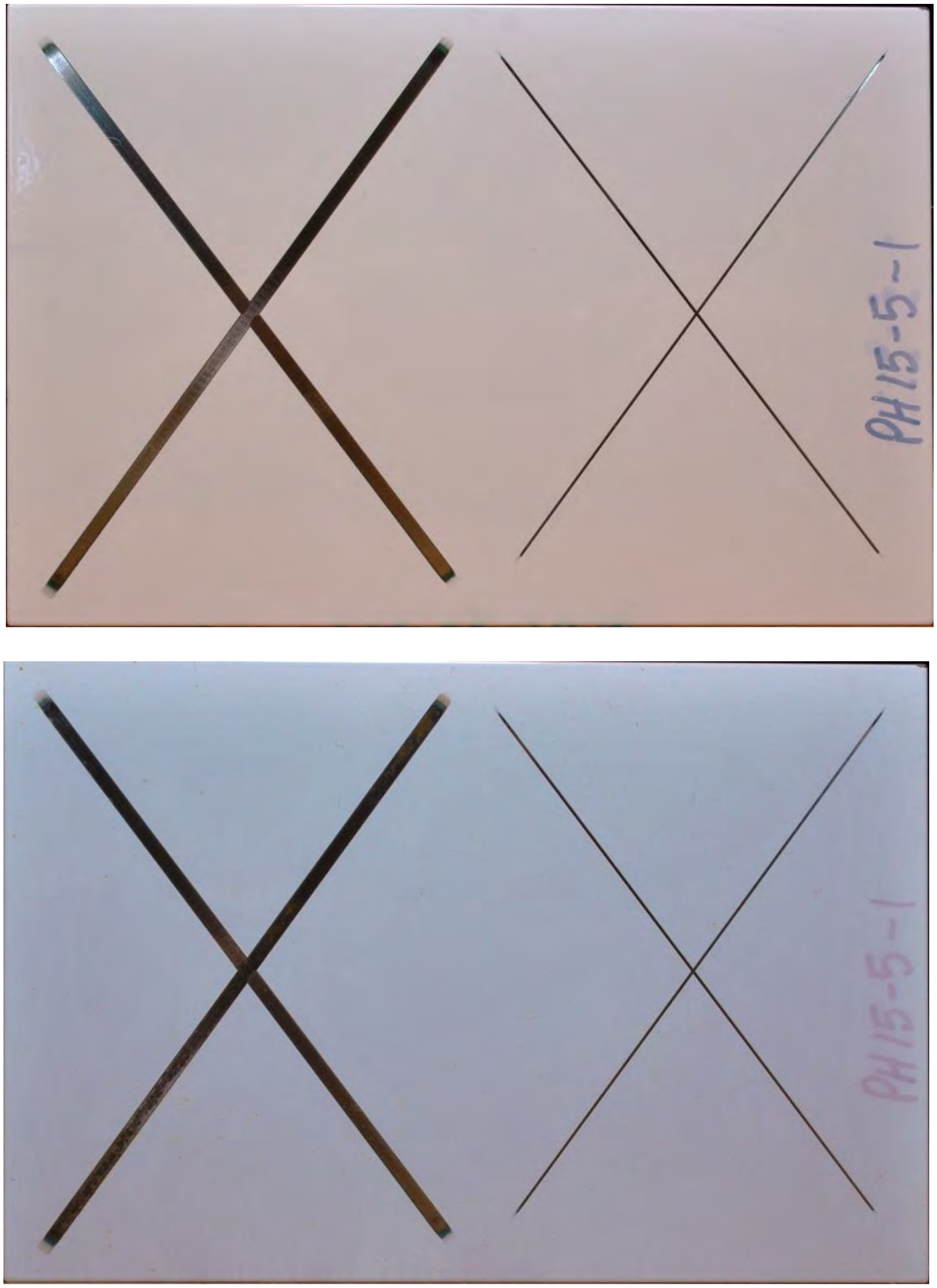

Figure 50 – UNS S15500 test panel with pre-primer, primer, and paint protection scheme prior to test (top) and after 500 hour test (bottom) per ASTM B117. Localized iron oxide corrosion product was present on the 2.5 mm scribe line. There was no blistering or undercutting of the protection scheme.

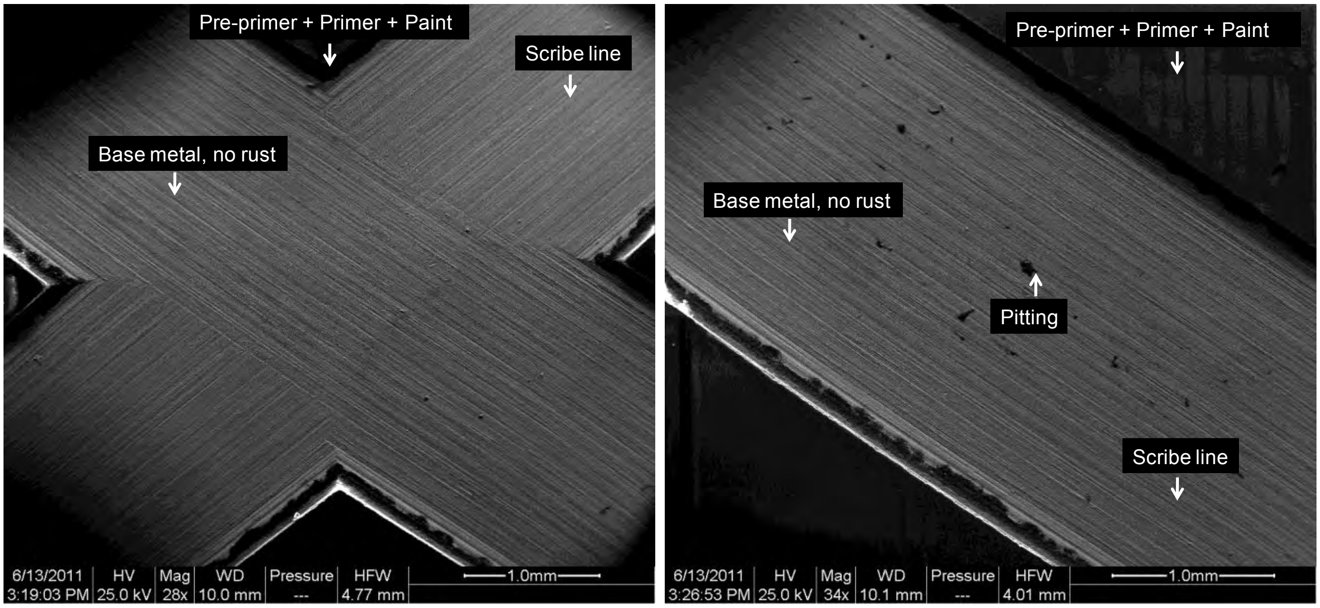

Figure 51 – SEM micrograph of UNS S15500 2.5 mm scribe after 500 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis. There was pitting observed within the length of the scribe.

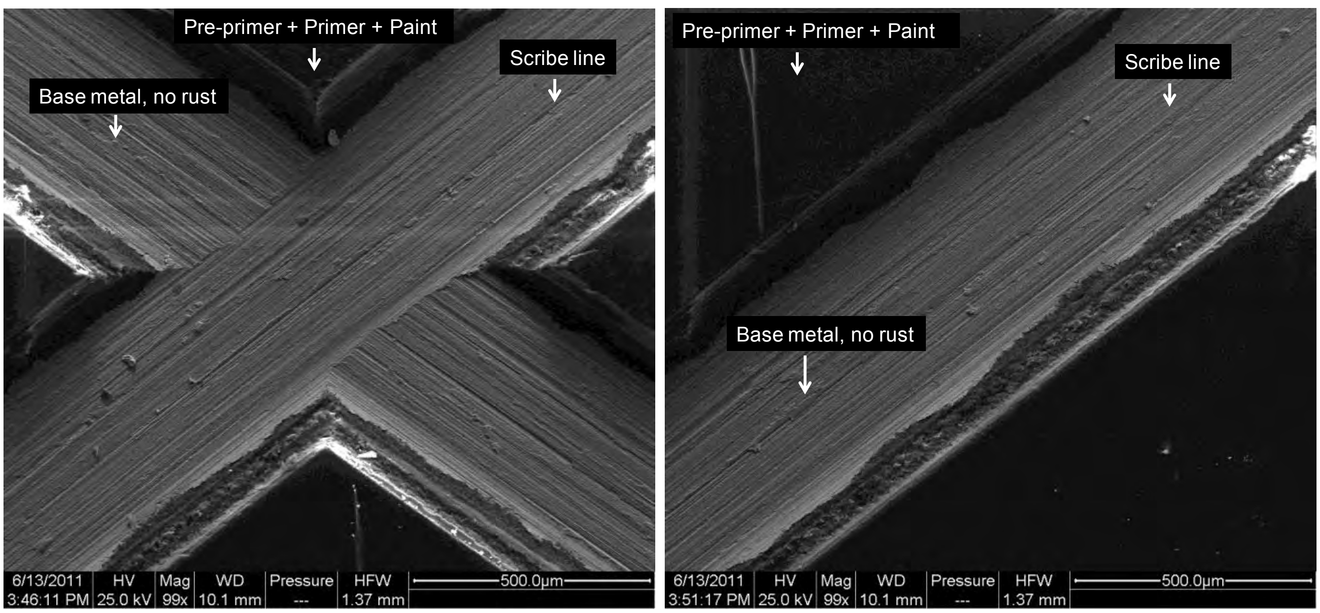

Figure 52 – SEM micrograph of UNS S15500 0.5 mm scribe after 500 hour test per ASTM B117. No blistering or undercutting of the protection scheme was observed during the analysis.

CONCLUSIONS

1. After 100 hours of salt fog testing per ASTM B117, the primer and paint protection scheme of UNS S10500 is comparable to that of cadmium, primer, and paint protection scheme of UNS G43400 and K44220. All three alloys and their respective protection schemes show the presence of localized iron oxide corrosion product without undercutting of the protection scheme.

2. After 500 hours of salt fog testing per ASTM B117, the primer and paint protection scheme of UNS S10500 is comparable to that of cadmium, primer, and paint protection scheme of UNS G43400 and K44220. All three alloys and their respective protection schemes show the presence of localized iron oxide corrosion product and some signs of undercutting of the protection scheme in the 2.5 mm scribed intersection.

3. After 100 and 500 hours of salt fog testing per ASTM B117, the cadmium protection scheme starts to break down as evidenced by the presence of iron oxide corrosion product in the low-alloy steels (UNS G43400 and K44220). However, the higher-alloy and corrosion resistant steels (UNS K92580, UNS K91973, and UNS S10500) provide additional corrosion resistance as there is no presence of corrosion product shown.

4. After 100 and 500 hours of salt fog testing per ASTM B117, the zinc-nickel protection scheme does not show the presence of corrosion product but starts to exhibit blistering of the protection scheme along the scribes. This blistering may be due to poor adhesion of the protection system that is evidenced by the large amount of zinc-nickel oxides present within the scribe, and may have potential for further optimization to reduce or eliminate the presence of blistering.

ACKNOWLEDGMENTS

Research was sponsored by Benet Laboratories on behalf of the US Army Contracting Command Joint Munitions & Lethality Contracting Center - and was accomplished under Cooperative Agreement Number W15QKN-09-2-0001. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of Benet Laboratories or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for government purposes notwithstanding any copyright notation herein.

REFERENCES

1. Joint Test Report (JTR) – Development of Ferrium S53® High Strength Corrosion Resistant Steel Through the Environmental Security Technology Certification Program (ESTCP) and the Strategic Environmental Research & Development Program (SERDP), March 2008.

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